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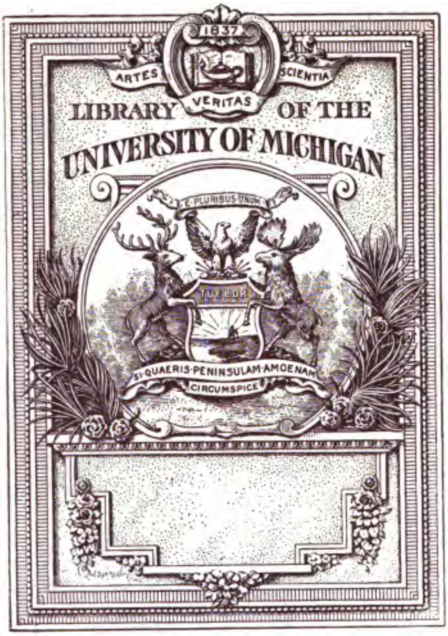
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ROCK-FORMING MINERALS.

BY

FRANK RUTLEY, F.G.S.,

Lecturer on Mineralogy in the Royal School of Mines.

WITH 126 ILLUSTRATIONS.

London:
THOMAS MURBY,
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1888.

PREFACE.

STUDENTS on the Continent are well supplied with text-books giving instruction in the more recent methods of petrographical research; but in this country it is otherwise, and those who wish for such teaching in their own tongue fare badly, unless they can attend lectures and devote their time to a course of systematic work in the laboratory. Even then there is a constant demand for a book to which they can refer for information enabling them to determine the chief rock-forming minerals. Yet, although many of the works now published supply them with much that is useful, this want seems still to remain unsatisfied.

It is essentially a student's want. Whether this book will in any way meet it, at least for the time being, is a question best answered by the book itself.

Text-books of mineralogy and petrology are, to a great extent, necessarily compilations from others bearing upon these or upon collateral branches of science. In the present case the Author has referred largely for information to the following works:—

Bauerman, H., "Text-book of Systematic Mineralogy" 1881.
" " " "Descriptive Mineralogy" 1884.
De Lapparent, A., "Cours de Minéralogie" . . . . 1884.
Groth, P., "Physikalische Krystallographie" . . . 1885.
Rosenbusch, H., "Mikroskopische Physiographie," Bd. i. . . . . 1885.
Tschermak, G., "Lehrbuch der Mineralogie" . . . 1884.

To the writings of Profs. Des Cloizeaux, Dana, Zirkel, Fouqué, and Lévy, the Author is, of course, also greatly indebted, as well as to those of the late Profs. Naumann and A. von Lasaulx. Numerous books by other authors have also been consulted; and the most grateful acknowledgments are tendered to several friends who have given important help in the correction and revision of the work.

Save in a very few instances, no references to original sources of information have been given, as they would have expanded the book far beyond its present limits. The more advanced student will find a copious bibliography in the work of Prof. Rosenbusch, already cited, and numerous references to the European and American literature of the subject in Mr. Teall's "British Petrography."

F. R.

NOTE ON PREPARATION OF MODELS.

With a few exceptions, models to illustrate the optical characters and the cleavage of the principal biaxial rock-forming minerals may be constructed from the figures given in the second part of this book. In doing this, it will be found most convenient to double the dimensions, copying the figures upon moderately stout cardboard. The separate pieces, when cut out, may be fixed together in their proper positions by means of coaguline, and they may then be mounted upon wooden match-ends fixed in holes bored in small, flat pieces of wood, which serve as feet. Each pinacoidal plane of the model should be inscribed with its proper symbol, and the label on the foot should be so placed that the plane corresponding to 100 should in every case face the observer. Such models will be found extremely convenient for reference, and the student will derive some benefit from their construction. In fixing the models, Kay's coaguline is much to be preferred to thick gum, as its sets more rapidly.

Errata.

PAGE
3 34, line 16 from bottom, for "α, β and γ," read "γ, β and α."
35 ,, 11 ,, ,, for "Chalunes," read "Chaulnes."
40 ,, 3 ,, ,, after "that" insert "on meeting the film of balsam."
57 ,, 6 and 7 from bottom, for "normal to these common tangent planes or circular sections of the ellipsoid" read "following these surfaces of the cones."
57, last line for "Ox Ox," read "The directions Ox," and for "external" read "internal."
58, top line for "Of these" read "Here."
58, line 3 from top, for "ex-" read "in-."
58 ,, 5 ,, ,, for "internal" read "external."
82, ,, 6 ,, bottom, before "optic," insert "traces of the"
92 ,, 11 ,, ,, for "thickening," read "thinning;" and for "greater," read "less."
92 ,, 7 ,, ,, for "thickening," read "thinning."
92 ,, 6 ,, ,, for "greater," read "less."
93, lines 6, 20, and 24 from top, for "thickening," read "thinning."
106, line 6 from bottom, for "on the basal plane" read "on a face of the cube."
107 ,, 10 ,, top, before "magnetite," insert "a moderate amount of."
114 ,, 16 ,, bottom, after "O_{12}," add "+ $2H_2O$."
125 ,, 16 ,, top, before "absence," insert "usual."
162 ,, 9 ,, bottom, for "(100)" read "(110)."
165, foot-note, for "Yarbuch," read "Jahrbuch."
167, line 16 from bottom, erase "hence."
195 ,, 20 ,, ,, for "of," read "between"; and for "axis," read "axes."
208 ,, 4 ,, top, for "*c c*," read "P P."
208, Fig. 105, for "C C," read "P P," insert *c* beside central dot on the line joining b b′, and erase "001."
Note.—In this figure the plane of projection is at right angles to the vertical axis *c*.
208, Fig. 106, for "*c c*," read "*c c*."
Note.—In this figure the plane of plane of projection is on s s′ in Fig. 105—*i.e.*, not quite parallel to the clinopinacoid, 010, which in Fig. 105 is parallel to P P.
218, line 6 from bottom, erase "not particularly"; for "but," read "and": and for "so," read "also strong."
219, Fig. 115, for "a," read "c"; and for "c," read "a."
2 233, line 9 from top, for "acute," read "obtuse."
3 221, Fig. 124, for "1̄01" read "101̄."
245, after "sphene," insert "Indices, $\alpha = 1{\cdot}8876$, $\beta = 1{\cdot}8940$, $\gamma = 2{\cdot}0093$, $2V = 23° - 34°$.

ROCK-FORMING MINERALS.

PART I.

I. Apparatus, Methods of Preparation, Examination, etc.

Before attempting the microscopic examination of a mineral or a rock, it is well to consider the kind of apparatus which will have to be employed.

We may, in the first place, deal with what is absolutely necessary for the simplest class of observations; in the next, with the means employed in the prosecution of the somewhat more advanced class of research; but the elaborate and costly instruments now used in the highest branches of petrological investigation will not be described, as they are beyond the reach of the majority of students. An account of such instruments and of the methods of using them will be found in Groth's "Physikalische Krystallographie" (2nd edition), in Rosenbusch's "Mikroskopische Physiographie der petrographisch wichtigen Mineralien" (2nd edition), and in other works devoted to this subject.

For the successful examination of a rock, an acquaintance with various branches of science is necessary, namely, chemistry, physics (especially optics), mineralogy, and geology.

Geology, indeed, may be regarded as the first essential, for, without it, we can find no real interest in rocks; and it is this science which gives us an insight,—often, however, only a rough or approximately true one, into the conditions under which a rock has been formed. Mode of occurrence is, therefore, a matter of immense importance in all petrological questions; and the eyes which see a rock only through a microscope will see but dimly where this first vision has been denied to them.

The general mode of occurrence of rocks will be found described in any good text-book of geology, and it is therefore needless to encumber these pages with an account of the principles, or of the more detailed explanations, relating to this branch of the subject. Suffice it to say, that the beginner going into the field should take with him a trustworthy geological map; while the experienced geologist will at least need a well-constructed topographical guide; preferably a map of large scale, cut into small pieces for the sake of portability and ready reference. With this, a strong hammer, a compass, clinometer, protractor, and collecting-bag, he will be able to do his work.

We shall also say but little about chemical reactions conducted under the microscope, since a practical acquaintance with the ordinary methods of analysis adopted in the laboratory is indispensable to the successful prosecution of this branch of research. Those, however, who wish for information upon the subject should consult Klement and Renard's "Réactions Microchimiques," Brussels, 1886, Bořický's "Elemente einer neuen chemisch-mikroskopischen Mineral- und Gesteins-analyse" (Prag, 1877), Fouqué and Lévy's "Minéralogie Micrographique" (Paris, 1879), etc.

A certain knowledge of mineralogy should also be possessed by any one who wishes to study petrology. For this purpose, however, after the general principles of the science have been learnt, an acquaintance with a comparatively small number of rock-forming minerals will suffice for the beginner; and, for information concerning minerals not given in the following pages, he is referred to the more recently published text-books mentioned in the Appendix.

From the foregoing observations, it will be seen that the student must have had some amount of preliminary training before he finds himself in a position to investigate the genesis, the changes, the chemical composition, and the mineralogical constitution of rocks.

The pocket-lens. When the observer has examined a chip of rock, and has seen all that he can see with his unassisted eyes, he should next have recourse to a lens; and it may here be remarked, that those who have had no practice in the use of this simple instrument, seldom hold it in a manner calculated to give it the requisite steadiness. To do this, hold the specimen in the left hand and the lens between the thumb and fore-finger of the right. Rest the tips of one or more of the remaining fingers of the right hand upon the specimen, and while keeping them in this position raise or lower the lens until the proper focus is gained. If the specimen be too small to afford a support to the fingers of the right hand, rest the disengaged fingers of the right upon those of the left hand. When a Coddington lens or one of very high power is employed, this precaution becomes additionally needful. Should it be necessary to scratch a minute crystal in order to test its hardness or streak, it will be found difficult to manipulate a knife and a magnifier at the same time. This difficulty can be obviated by employing a watch-maker's lens, held in the eye; but it is less fatiguing to use a small lens attached to a spring-clip which can be placed on the nose. The hands are thus left free.

The same end may be attained by adopting the contrivance used by engravers; namely, by fixing one end of a stout brass wire round a watchmaker's lens of suitable focus. The other end is turned into a small loop, and the wire is then bent to about two-thirds of a circle, so as to fit comfortably round the head. There is thus sufficient spring in the wire to keep the lens in position without any muscular effort whatever; and it can be shifted on to the forehead and replaced over the eye without trouble.

Specific Gravity.—The determination of the specific gravity of a rock, or of any of its component minerals, may be effected in the ordinary way by means of a suitable balance; but larger masses may be employed when Mohr's apparatus is used, a considerable advantage when rocks composed of more than one kind of mineral are being examined. The latter consists of a burette with its usual support. Beneath the lower end of this a tall glass cylindrical vessel 3½ to 4 inches in diameter is placed, and across its mouth is laid a strip of wood through which a large needle is driven, fitting so that it can be easily slid up or down. A piece of india-rubber tubing is then attached to the superior extremity of the burette, water at a temperature of 60° F. is poured into the glass cylinder beneath it, and the needle so adjusted that its point barely touches the surface of the water, the reflection of its point appearing to touch the actual point of the needle. The specimen, having been accurately weighed in air, is now immersed in the water, which rises in the cylinder. The operator next applies his mouth to the tubing connected with the upper end of the burette, the lower end being adjusted so as to be well below the level of the water in the larger vessel, opens the tap on the nozzle and draws up into the burette a slightly greater quantity of water than the specimen displaced, so that the water stands a little below the point of the needle, and closes the tap. He next opens the tap cautiously, allowing the water in the burette to drip back into the cylinder until the original level (*i.e.*, up to the needle-point) is restored. The amount of water displaced by the stone, is now in the burette, and can be ascertained by means of the graduation. If then we divide the weight of the mineral in air by the weight of the displaced water in the burette, we get the specific gravity of the specimen, with only such slight error as may be due to the adhesion of water to the sides of the glass vessels employed. Walker's balance is another instrument well suited for this purpose, and capable of giving rapid and satisfactory results. Jolly's spring balance, although less portable, may also be employed with advantage, when the specimen is small and light, *i.e.*, about 8 grammes or less. To the delicate spiral spring of the instrument pans are attached, so that the substance examined requires no thread for its support, and can be used even in small fragments. Where greater precision is required, the older method, in which a chemical balance is employed, will be found more satisfactory; but it is advisable to immerse the specimen in water for a considerable time, or else to boil the water in which it is immersed, so as to displace any air within the stone. The specific gravities of the constituent minerals of roughly pulverized rocks may also be determined by means of a solution of known density,* such as Thoulet's or Sonstadt's solution. This can be diluted with water without undergoing any appreciable change of volume, so that solutions of any desired lower density than 3·19 can be procured. Other solutions are also employed for the same purpose.

Sonstadt's Solution.—Iodide of potassium and mercury.

Maximum sp. gr. = 3·196 (Goldschmidt).

Minerals with a density of more than 3·2, such as Olivine, Augite, etc., cannot of course be separated from one another in this solution.

Klein's Solution.—Boro-tungstate of Cadmium.

Maximum sp. gr. = 3·28.

All carbonates should be removed from the rock-powder by acids before separation, since, if present, they would decompose

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* The author is indebted to Mr. Grenville A. J. Cole, F.G.S., for the revision of pp. 4 to 12.

the solution. The salt, though poisonous, has not the corrosive properties of Sonstadt's solution.

Methylene Iodide (recommended by Brauns).

Maximum sp. gr. = 3·34.

This solution discolours when exposed to light, and must be diluted with Benzol. It can be rendered pale yellow again by shaking up with mercury, and has the great advantage of not crystallizing out when cooling after concentration upon the water-bath.

Rohrbach's Solution.—Iodide of barium and mercury.

Maximum sp. gr. = 3·58.

This solution becomes so readily decomposed in presence of water that its use is very restricted. The powdered minerals to be separated must be thoroughly dried before being placed in the solution.

Bréon's Mixture, produced by the fusion of chloride of lead with chloride of zinc in various proportions, is at times employed for the separation of rather coarsely pulverized minerals, whose specific gravities range from 2·4 to 5.

The mixture is fused in a small tube placed in a sand-bath —perfect mixture occurring at about 400° C. The powdered minerals are then stirred in with a platinum rod, when the heavier particles sink to the bottom of the tube while the less dense ones remain at the top. The test-tube, having been allowed to cool a little, is plunged into cold water, and the upper and lower portions of the fused column are detached and separately dissolved in hot water to which nitric acid is added. The minerals thus separated, when washed, are ready for analysis. Fused Boro-tungstate of Cadmium similarly employed gives a density of 3·6.

Glass vessels of various kinds are used, when Sonstadt's, Klein's, or Rohrbach's solutions are employed. For the first separation an ordinary separating-funnel is generally found convenient; but more delicate separation may be effected by means of other apparatus, especially that devised by Harada, and manufactured by Kramer, of Freiburg in Breslau.

This consists of a small pear-shaped glass vessel, the upper end of which is closed by a stopper while the lower part is prolonged into a tube, a small glass stop-cock shutting off the bulbous from the tubular portion of the apparatus.

The stop-cock being closed and the stopper removed from the upper orifice, the solution (Klein's or Sonstadt's) is now poured in and the powdered minerals are added. The stopper is then replaced and the apparatus well shaken. The minerals now separate according to their respective densities, as indicated by the stippling at *x* and *y* in Fig. 1.

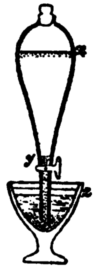


Fig. 1.

A small conical test-glass is next placed below the tube, so that the end of the latter nearly touches the bottom, and the stop-cock is cautiously opened. Some drops of the solution now pass into the test-glass, carrying with them the heavier powdered minerals which were lying at the lower end of the vessel. The stop-cock is then closed, and a little water is poured into the test-glass and floats in a thin layer (*z* Fig. 1) on the solution. The apparatus is then gently raised, until the nose of the tube is brought into the stratum of water, when the remainder of the solution with its contained powder passes into the test-glass, while the water rises into the tube as far as the closed stop-cock. Further details of manipulation will be found in the latest edition of Rosenbusch's "Mikroskopische Physiographie," vol. i., Stuttgart, 1885, where a description of Westphal's balance, specially devised for determining the density of the solutions, is also given.

In Brögger's modified form of this apparatus the separation may be still more perfectly effected, a second stop-cock being introduced about the middle of the apparatus, which, in this altered form has a less bulbous configuration (*op. cit.*, p. 216). In practice a rubber tube and clip can often be substituted for a stop-cock in the funnel employed.

The value of such solutions in effecting the separation of the minerals in a crushed sample of rock is very evident. If, for example, some pulverized diorite be thrown on the surface of a solution having the density 2·75, the felspars will remain there, while the hornblende, magnetite, apatite, etc., will sink. In this manner small fragments of a particular mineral may be isolated for analysis, provided that a sifted sample has been selected of such fineness that each particle consists of one mineral species only. The student will find it useful to construct a table of the principal rock-forming minerals, ranging them according to their respective specific gravities. This may easily be done from the tables given at the end of this work.

Fusibility.—The fusibility of a rock is, of course, dependent upon its chemical composition, or upon the nature of the minerals of which it is composed. All experiments made upon the fusibility of rocks before the blowpipe, should be conducted not upon large fragments, but upon the edges of very thin splinters; and where the rock is at all coarsely crystalline, a kind of selective fusibility,—if one may use such an expression,—is often to be observed, the phenomena being dependent upon the different grades of fusibility of the minerals present in the rock. A good natural example of this is seen in hornblendic gneiss when it has been struck by lightning, the hornblende on the surface being fused to a dark-brown glass, while the felspar is converted into a white frothy glass.

Flame Reactions.—These are often of considerable value in ascertaining the presence of certain minerals which contain substances that impart more or less characteristic colours to the flame either of a blowpipe or of a Bunsen's gas jet.

The method adopted by Szabó is of especial use in determining the different felspars by means of the extent and intensity of colour communicated respectively by the alkalis K and Na. In this process a Bunsen's burner is employed (Fig. 2, *a*.), provided with a small chimney of sheet-iron (*b*) which is supported by a little brass casting or gallery (*c*) of spokes radiating from a ring, which can be adjusted by screwing it on a thread cut on the tube of the Bunsen's burner. This should be so arranged that the chimney hides about a fifth of the flame at its base. The remainder of the apparatus consists of an upright rod (*d*) fixed to a heavy foot, and having a small arm or wire projecting at right angles from the rod and capable of being easily raised or lowered by a sliding motion. Upon this arm a little piece of glass tubing (*e*) is slid, being drawn out at one extremity to a point, in which a very thin piece of platinum wire is fused, the projecting end of the wire being bent into an extremely small loop to support the assay. All being in readiness, a very diminutive splinter of the felspar to be examined is taken up on the loop of platinum wire, which should be previously moistened with distilled water. The felspar fragment should be about the size of this dot (•) The assay is then brought very cautiously near the flame, the splinter resting on the upper side of the loop. It should thus be gradually heated until there is no longer any probability of decrepitation, and

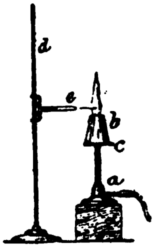
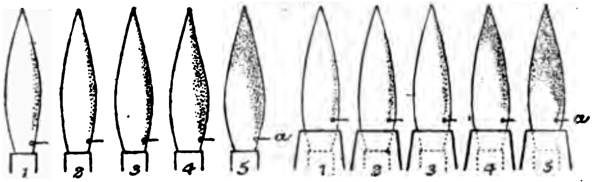


FIG. 2.

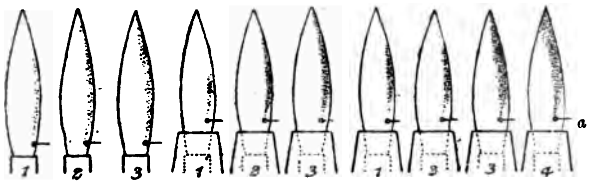
it should then be rapidly transferred for a few seconds to the hottest part of the flame, about the apex of the blue inner cone, when the felspar fuses and adheres to the wire. It should now be withdrawn, and the arm supporting the wire so arranged that the assay can at once be brought into the outer envelope of the flame at a point 5 millimetres above the orifice of the Bunsen's burner, no chimney being used. The assay when thus introduced will be seen to communicate a more or less intense yellow colour to the flame; and this colour will pervade a greater or less portion of the flame according to the amount of sodium present in the felspar. Five tolerably well-defined grades of coloration may be distinguished in this first trial for sodium, the first grade being merely a yellow coloration of one edge of the flame; this, in the higher grades, increases in intensity and extent until about three-quarters of the flame become strongly yellow. The first grade indicates 0·5 to 1% Na; the second, 1 to 2%; the third, 2 to 4%; the fourth, 4 to 8%; and the fifth, 8 to 16%. The mineral should be withdrawn at the end of one minute. In the second trial, also lasting one minute, the chimney is placed so as to surround the lower part of the flame, and the assay is now introduced a little above the chimney, nearly on a level with the point of the blue inner cone, and is inserted rather further into the flame than in the previous trial. Five grades are recognised in this second experiment. In the third, the same conditions are observed, only the assay is previously coated with a little pure and finely-powdered gypsum, and the operation conducted for two minutes. The maximum yellow coloration may here be reached, and it may extend over the greater part of the flame.

The trials for potassium are conducted in a similar manner, and side by side with those for sodium, the flame being viewed through, first one and then a second thickness of glass coloured blue by cobalt, or through a strong solution of indigo or aniline blue in a cell 4 centimetres thick. By this means the yellow of the sodium flame is abolished. In the first trial for potassium, in the outer envelope of the flame, there are three grades, ranging from a marginal tinge of red to a coloration of about one-third of the flame. In the second trial, there are also three grades or intensities; and in the third, when gypsum is added, which brings the alkalies into the condition of sulphates, and renders them more volatile, there are four—the red-violet coloration, in the extreme phase, extending over more than half of the flame.

In this third trial the two first grades denote plagioclastic, and the two last orthoclastic felspars. The foregoing observations will perhaps be rendered more intelligible to the student by the following diagrams (Fig. 3). In the upper line of flames the extent of the yellow coloration produced by Na is indicated by stippling, while in the lower line of flames the stippling denotes the extent of the violet coloration seen through blue glass when K is present. The levels at which the assay is inserted in the flame are shown in the figures by the letter *a*. The different intensities of colour are approximately indicated by the numerals placed below the diagrams.



Na. 1st Trial. Na. 2nd and 3rd Trials.



K. 1st Trial. K. 2nd Trial. K. 3rd Trial.

Fig. 3.

The following table, which is an abbreviated version of that given by Dr. Szabó,* shows how the results may be recorded.

	1st Trial.		2nd Trial.		3rd Trial.	
	Na. 1–5	K. 1–3	Na. 1–5	K. 1–3	Na. 1–5	K. 1–4
Adularia	1–2	3	2–3	3	2–3	4
Microcline	2–3	3–2	2–3	3–2	3	3–4
Albite	5	0	5	0	5	0–1
Oligoclase	5–4	0	5–4	0	5–4	1–2
Andesine	4–3	0	4–3	0	4–3	1–2
Labradorite	3–2	0	3–2	0	3	1–2
Bytownite	3–2	0	3–2	0	3–2	0–1
Anorthite	2–1	0	2–1	0	3–2	0–1

The relative fusibility and the product of fusion of the assay should be noted after each operation, the examination being made with a lens.

The Microscope.—Of late years the microscope has proved itself to be as indispensable to the petrologist as his hammer; but, as it is not every kind of hammer that is suitable for stone-breaking, so it is not every kind of microscope that will fulfil the requirements of the mineralogist and petrologist.

Without entering into lengthy descriptions of the different patterns of microscope now made, it may be well to direct the student's attention to certain matters of importance bearing upon the construction of an instrument specially destined for petrological or mineralogical researches.

A microscope dedicated to these uses should of course possess the indispensable attributes of any good microscope, namely steadiness in its supports, steadiness of stage under reasonable pressure, smoothness and absence of back-lash in

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* "On a New Method of Determining the Felspars in Rocks." Proceedings of American Association for Advancement of Science. Vol. XXXI.

the adjustments, and achromatism and absence of spherical aberration in the lenses. The question whether the microscope should be monocular or binocular is of comparatively small importance. For a certain limited class of work, a binocular arrangement may be desirable; but, as a rule, the monocular form is the more convenient. Extremely large microscopes present but few advantages to compensate for their inferior portability; while, on the other hand, very small instruments, unless clamped to a table, shift about, owing to an insufficiency of metal; and this is a rather serious objection to their use when microscopic drawings have to be made. Generally speaking, a sub-stage is unnecessary.

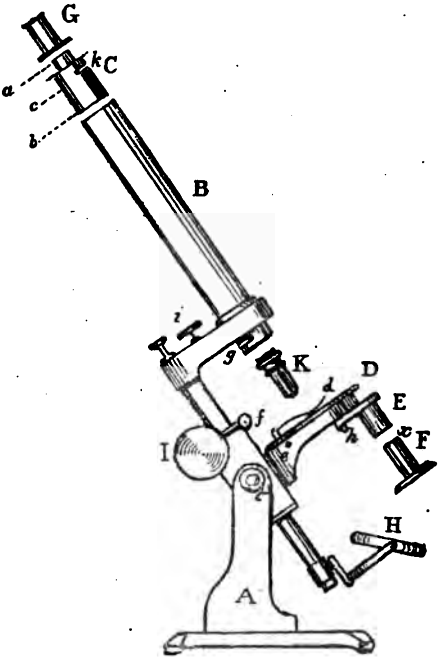

Fig. 4.

Before describing the different parts of a microscope, it may be useful to any one who is not familiar with the instrument, to name them and indicate their relative positions. This will be best done by referring to Fig. 4, in which, A = the foot and B = the tube.

In the different patterns of microscope, the parts connecting the tube with the foot vary considerably. In those in which the instrument is capable of being placed in an inclined position, the body of the microscope is connected with the foot either by means of trunnions, *t.t*, or by a simple joint.

C = The eye-piece. This is usually of the kind known as negative, or as Huyghens' eye-piece. The two plano-convex lenses,—of which the upper one (*a*) is termed the eye-glass and the lower one (*b*), the field-glass,—have their convex surfaces directed downwards. Within the focus (*c*) of the eye-glass, two fine wires or spider-lines are inserted. These should intersect accurately at right angles. Two slots (*k*) may be cut in the tube well above the level of the spider-lines, either through the upper right and lower left, or through the upper left and lower right quadrants, to permit the insertion of a quartz-wedge in such a manner that its longer axis makes angles of 45° with the crossed spider-lines. In Nachet's microscope there is a special arrangement for illuminating the latter; but this, although advantageous, is not, as a rule, necessary.

G = The Analyser (eye-piece analyser), consists of a Nicol's prism mounted in a brass fitting which slides over the upper end of the eye-piece and can be easily rotated. At the lower extremity of the fitting is a divided disc. The divisions, however, need only mark eight equidistant points, one of which must accurately coincide with the principal section (*i.e.* the shorter diameter) of the Nicol. These eight points enable the observer to place the principal section of the analyser either at right angles to, parallel to, or at an angle of 45° to the principal section of the polarizer F. When the eye-piece analyser is not in use, a perforated brass cap is placed over the eye-piece, to prevent reflection from the surface of the eye-glass and to cut off extraneous light. To effect the latter object more completely, the cap of the eye-piece is sometimes provided with a cup-shaped opening; but the same purpose is better answered by fitting a disc of cardboard about four or five inches in diameter round the tube of the cap, cutting out a hollow to accommodate the observer's nose, and covering the disc with dark velvet.

The eye-pieces are usually either lettered or numbered. The A eye-piece, or No. 1, being the one generally employed, and having the lowest magnifying power. B, or No. 2, and C, or No. 3, etc., give higher amplifications; but their use entails a slight loss of definition and, with the deeper eye-pieces, a very considerable loss of light. When the student possesses only two or three objectives the B and C eye-pieces will be found useful for giving intermediate and higher amplifications; and even where the available range of objectives is large they will be found convenient at times. The spider-lines should be fitted in the A, or No. 1, eye-piece, which should also be slotted to receive the quartz-wedge and be so arranged that it can carry the eye-piece analyser. The A, or No. 1, eye-piece is, in fact, the one most commonly in use.

g = a tubular fitting with a slot to receive the quarter undulation plate, the Klein's quartz plate, or the lens for enlarging interference figures. Into the lower end of this fitting is screwed the objective K.

The objectives are, relatively, the most expensive portions of the microscope. There are, however, good and cheap objectives both of English and Continental manufacture, which, if carefully selected, will, as a rule, answer the requirements of the student perfectly well. Wide angular aperture is not generally needed for petrological work, the main desiderata being achromatism, good definition, penetration, and flatness of field.

The following selections will be found useful. They are arranged according to the number of objectives with which the student intends to provide himself.

3 objectives 1½ inch, ⅔ inch, ¼ inch.
4 „ 2 inch, 1 inch, ½ inch, ¼ inch.
5 „ 3 inch, 2 inch, 1 inch, ½ inch, ¼ inch.

Intermediate and higher objectives are at times desirable, but they are not, as a rule, necessary.

D = The Stage. This should be firm and steady under moderate pressure, such as may be reasonably exercised in moving a slide about by hand.

One thing necessary in a microscope intended for mineralogical and petrological work is, that the stage should rotate, and that there should be some means of bringing the axis of rotation into coincidence with the axis of vision. For a microscope provided only with a couple of objectives, one of high, or moderately high, and the other of low power, the accurate centring of the stage with the higher power can be easily, but permanently, effected by the maker of the instrument; and in this case any little imperfection in the centring when the lower power is employed, is, as a rule, of comparatively small consequence. Most students, if provided with such an instrument, will, however, sooner or later find it needful to use a more complete range of objectives, and it will then be found that, owing to unavoidably slight differences in the manufacture, scarcely two can ever be found which will not, when used with an ordinary microscope, require a slight shift either of themselves or of the stage, in order to make the rotation of the latter concentric with the axis of vision.

This concentricity may be brought about either by having a centring arrangement for the stage or a centring arrangement for the objective. The latter, although the less satisfactory, is the cheaper, and consists of a separate piece of apparatus known as a centring nose-piece, which is screwed to the lower end of the microscope-tube and is tapped at its inferior extremity to receive the thread of the objective.

Whether nose-piece or stage be arranged for centring, the process is effected by means of two screws terminating in small milled heads, which, when turned, give a backward or forward motion to the stage in directions at right angles to one another.

Let *a*, Fig. 5, represent an object lying exactly in the centre of the field. If the centring of the microscope be perfect, it will remain in the same spot during the rotation of the stage; but, if the centring be imperfect, the object will travel more or less from the point *a*. Assume that it describes the circle *abc* then *c* will be the remote point at which the circle *abc* cuts the line *tw*, one of the directions in which the stage can be moved by the centring screw *x*. Now, when the object is at the point *c*, turn the milled head *x*, so as to move the stage in the direction of the arrow towards *t* until the object has moved through half the distance *ac*, the spot indicated by the small cross marked *d*. Then, without again touching the centring screws, move the slide on which the object is mounted, by means of the fingers, until the object again occupies the exact centre of the field (the point at which the spider-lines *l l l′ l′* in the eye-piece intersect). Again rotate the stage; and we will assume that the object now describes the circle *abc* Fig. 6.

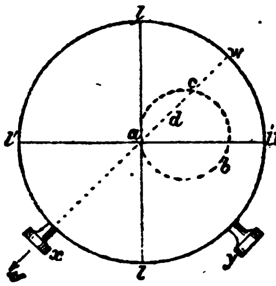

FIG. 5.

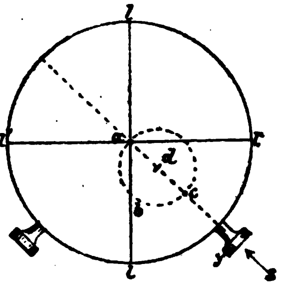

FIG. 6.

In this case the milled head *y* must be turned so as to move the stage in the direction of the arrow towards *r* until the object has moved from the point *c* to the point *d* (*i.e.* half the distance *ca*). Once more adjust the slide on the stage so that the object again lies at the point where the spider-lines cross. Should the operations have been accurately performed, the object will no longer travel away from the centre of the field when the stage is rotated. In this respect the microscope made by Nachet of Paris, has a great advantage over every other instrument yet manufactured, inasmuch as no centring arrangement is needed, since the limb, carrying the tube of the microscope and the objective, is attached to the stage, and travels round with it, while the polariser and analyser work independently and do not share in the rotation.

The other points in which petrological microscopes differ from those of ordinary construction are not very numerous, but they are important. The stage should be divided in degrees. For very exact work, the circle may be divided to half degrees, and a vernier may be employed; but for ordinary work it will be found more convenient to adopt the division into degrees only. The edge of the stage should be coarsely milled; or it may be provided with small projecting knobs or cogs on which the finger readily catches.

Mechanical traversing arrangements for the object-carrier are rather an encumbrance than an advantage. The most generally useful contrivances are spring clips, *d*, Fig. 4, beneath which the slide is readily secured and moved about by hand. In Fig. 4, *e* represents the squared end of one of the centring screws; the keys with milled heads, which fit on to them, being removed and stuck into a small tubular fitting at *f* when not in use. The disadvantage in having the heads permanently attached to the screws is, that in adjusting an object on the stage, they are frequently touched by accident, and the centring process then has to be repeated. To the under side of the fixed part of the stage, and *not participating in its rotation,* is a small pivot *h,* upon which turns an arm with a tubular fitting, made to receive the polariser F. At the lower end of the tube which immediately surrounds the prism, is a disc similar to that at the base of the analyser, also bearing eight equidistant lines, while four slight holes are drilled corresponding with four of the alternate divisions. A tubular collar, carrying an index, fits outside the first tube, and a small stud screwed through the index clicks in the four little depressions when the disc is rotated, and acts as a stop. The principal section of the polarising Nicol must accurately coincide with the line joining one pair of these depressions when the stop is clicked.

The arm carrying the tube E, which receives the polariser, can be turned so that the latter comes immediately beneath the well or aperture in the stage, a stop being provided to prevent it from passing too far. By this arrangement the polariser can be turned out of the way when not required. The tube surrounding the prism should be long enough to slide some distance up the aperture in the stage.

Two small, almost hemispherical lenses, of which the upper one should be easily removable, Fig. 7, *x,* mounted in a suitable fitting, drop into the upper end of this tube (at *x* fig. 4); and the plane surface of the upper lens should, when the polariser is pushed up, be on a level with the surface of the stage, so that it almost touches the glass slide on which the preparation is mounted. These lenses serve as a condenser for supplying a convergent pencil of light when the interference figures of crystals are under investigation. When they are used, a quarter-inch objective should be employed, and the eye-glass and field-glass of the eye-piece should be

FIG. 7.

removed, or an empty brass eye-piece fitting should be substituted, over which the eye-piece analyser is placed. Seen under these circumstances, the interference figures are extremely small; but they may be greatly enlarged by the insertion of a lens of low curvature a little above the objective, or by the use of an eye-piece to suit the vision of the observer When in such investigations it is needful to cut off the images of extraneous objects in the field, a small metal cap, perforated by a pin-hole, is placed over the condensing lenses.

H, Fig. 5, is the mirror, usually plane on one side and concave on the other; and from this the light is reflected up the tube of the microscope. I, Fig. 5, is the milled head of the coarse adjustment, and *i* that of the fine adjustment, both of which serve to bring the instrument into focus. With low powers the fine adjustment is not needed. With high powers the coarse adjustment should be used with great caution, or there will be danger of running the objective through the preparation and damaging both.

In this brief sketch of the general characters of a microscope intended for the investigation of minerals and rocks, several pieces of apparatus have been mentioned without any account being given of the purposes which they subserve, or of the way in which they are used. Further particulars about them will, however, be given as the methods of research are gradually explained. Descriptions of the various patterns of petrological microscopes now in use would be out of place in this small treatise. Good instruments, suitable for the purpose, are made in this country by Swift, Watson, Beck, Crouch, and others, while on the Continent, the microscopes of Nachet, Voigt and Hochgesang, Fuess, and Hartnack are those generally in use. Among the best objectives made on the Continent, may be mentioned those of Zeiss, Hartnack, and Seibert. The latter, if employed with English microscopes, generally require an adapter, as they carry a different thread.

The student's microscope should be provided with a strong case; and the fittings in it should be fixed with screws from the outside, as in gun-cases. When glue only is used, the fittings sometimes get detached during a journey; and under these circumstances the instrument may sustain severe damage. The handle of the case should not be a thin brass one, or it will be found to hurt the fingers when the microscope is carried for more than a short distance, unless the instrument be a very light one. For artificial illumination any small paraffin lamp will serve. The usual microscope lamps, supplied by the opticians, answer perfectly well for all ordinary purposes. For examining objects by reflected light, a bull's-eye condenser is necessary. This should be fitted on a separate stand the foot of which unscrews, so that it can easily be packed. Examination by reflected light is often of the utmost importance in petrological research; and the student who neglects it is liable to fall into grievous errors.

Thin sections. If we put a piece of roughly broken rock on the stage of the microscope, protecting the latter, of course, with a strip of wood, a piece of cardboard, or a fold of cloth, we shall probably gain but little information regarding its mineral constitution, less about its structure, and little or none concerning its origin. The microscopic examination of road-metal, therefore, as we meet with it in our streets, is not altogether encouraging. It is necessary to cut thin slices of stone before satisfactory information can be elicited from it under the microscope.

There are two ways of procuring microscopic sections of minerals and rocks. The simpler, but more expensive one, is to send the specimens to some lapidary who is used to this kind of work; the other is to grind the sections one's self. Various machines have been devised for this purpose—some worked by a treadle, others by hand. These are not absolutely necessary. Good sections may be prepared from thin chips, flaked from a piece of rock with a small hammer, and ground down upon a leaden or cast-iron slab with emery and water. The process, however, of grinding down irregular chips is somewhat laborious, and it is desirable to employ a machine for cutting thin slices of stone, which require but little grinding to fit them for microscopic examination. Such a machine may be made on the pattern of an ordinary lapidary's wheel. The principle of its construction is shown in plan in Fig. 8, where A represents a large wooden disc, turned upon an axle B by means of a knob C, which serves as a handle. The edge of this disc is grooved to receive a band, which passes round a very much smaller wheel attached to the spindle *e*, which carries at its upper end, and about on a level with the large wooden disc, a thin disc of sheet iron, fastened by a nut which screws on to the end of the spindle and is tightened up by means of a spanner. The edge of this disc is charged with diamond dust and oil, the paste being carefully applied to an inch or two of the edge at a time, and then pressed into the soft iron with a burnisher or a smooth piece of agate. On a round iron pivot, *i*, fixed to an upright, is hinged a strip of stout iron plate, *h*, through which two holes are bored, and through these holes pass two pieces of iron rod, which are riveted to another

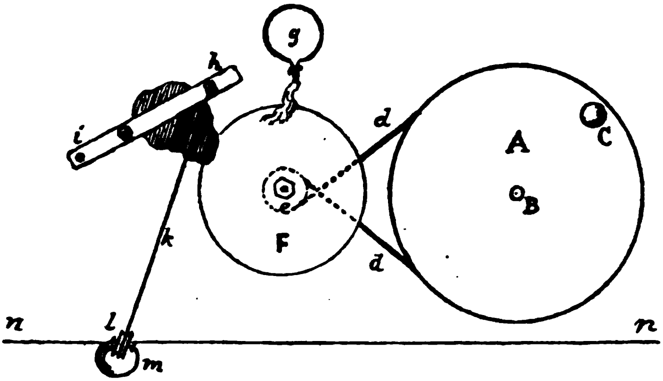

Fig. 8.

strip of stout iron plate. Each rod is tapped with a thread, on which, after it has been passed through the hole in the strip *h*, a nut is screwed. The piece of stone to be cut is placed between the jaws formed by the two strips of iron, and the nuts are then tightened up so as to grip it firmly. A string, *k*, is next tied to one of the jaws, and is passed over a small pulley, *l*, fixed on the edge of the table *n n*, a weight, *m*, being suspended from the end of the string, so as to draw the clamped stone against the edge of the slitting disc. A small vessel, provided with a little tap, is placed near the edge of the slitting disc. Into this vessel a solution of Castile soap is poured, and a few strands of cotton are so arranged that they form a communication between the tap and the edge of the slitting disc, keeping the latter constantly lubricated, and all is now in readiness for work. Care should be taken not to commence operations upon a jagged edge of the stone, otherwise the diamond dust will be stripped from the edge of the disc. The motion of the large wooden disc should be slow. Slices as thin as a piece of stout cardboard may be made with a machine of this kind. After the slice has been cut, it is necessary to grind it still thinner; and the processes about to be described are equally applicable to thin chips as to thin slices of minerals and rocks.

Two perfectly flat grinding slabs should be procured; the one of lead or cast-iron, on which rather, but not very, coarse emery is smeared with water; the other of brass, or, in its stead, thick plate-glass, on which only the finest flour emery is used, mixed with water. It is important to keep these two slabs well apart, so that no grain of coarse emery may reach the slab on which the fine emery is used.

If a chip be taken in hand, a flat surface must first be ground on it with coarse emery. It must then be thoroughly washed, to clear it from all coarse emery mud, and the flat surface should then be ground as smooth as possible upon the second slab with fine flour emery. Having washed the chip perfectly clean, the next process is to cement it on a piece of plate glass, which will serve as a handle while grinding the other surface. Again the coarse emery is employed, until a second surface, parallel to the first, is procured, and the two surfaces approach so closely that light is transmitted through the section. As soon as it becomes riskily thin, the grinding with coarse emery should be abandoned, the section thoroughly washed, and the grinding process continued with fine emery until the section appears, when washed and placed under the microscope, to be as thin as mechanical skill can make it. Often, by not daring to grind the section thin enough, a worthless slide is procured; and equally often, by too much daring, the entire section vanishes. Between these evils lies the happy, diaphanous mean, which insures a really good section.

Transferring the Section. The apparatus now needed consists of a small tripod, a piece of sheet iron or brass to lay upon it, a spirit lamp or a Bunsen's burner to put beneath it, a watch-glass standing in a pill-box lid, and containing a few drops of turpentine, one or two small camel's-hair brushes, an iron skewer filed off so as to afford a flat end to push with, a darning-needle stuck in a pen-holder, some Canada balsam, glass slips and thin covering glasses, also a pair of small tongs terminating in two flat pieces of cork, and a little pair of forceps.

These things being conveniently arranged, the lamp under the metal plate is lighted, and the small glass slab bearing the section is placed upon the plate. When sufficiently heated to liquefy the balsam with which the section is cemented, the glass slab is slid slightly over the edge of the metal plate, and the operator holds it firmly with the cork tongs in his left hand. With his right he takes the blunt-ended pushing bar, which he places against the edge of the section, and slides it off the glass slab into the little turpentine bath. Here he leaves it awhile, now and then gently warming the bath by holding it cautiously over the hot plate or over the lamp, care being taken that the turpentine does not ignite. He then takes the small camel's-hair brushes and washes the section very gently with them. A glass slip is now placed on the hot plate, which should not be too hot, and when it has been warmed, it should be placed on a sheet of paper, and a drop of balsam allowed to run on to the middle of it. The section is then lifted carefully out of its bath by means of the darning-needle, to the side of which it will readily adhere, and it is brought over the drop of balsam on the glass slip and allowed gradually to rest on it. When slightly warmed, the cushion of balsam spreads out beneath it, and another drop of balsam is allowed to run on to the upper surface of the section. A thin covering-glass, previously cleaned, is next taken in the forceps, and very slightly warmed near the flame. It is then placed over the section, resting first on one edge, and is allowed gradually to subside when the section is warmed. It should next be pressed firmly down, so as to squeeze out all superfluous balsam, and the preparation can either be placed in a drying oven, or be left to dry gradually. When the superfluous balsam is sufficiently set, so that a crumb of it can be rolled in the fingers, it may be cleared away with a penknife blade broken off square, the smears of balsam being ultimately cleaned off with a piece of rag or silk moistened with benzol. The preparation should then be labelled, or the name may be written on the end of the glass slip with a writing diamond.

Suitable boxes and cabinets for holding microscopic preparations may be procured from most opticians. The sections should lie flat; but if boxes with vertical racks only can be had, they should be placed on end, like books on a shelf, so that the sections will still lie horizontally.

Methods of Examination.—There are several methods of examining sections of minerals and rocks under the microscope.

(i.) *Examination by Reflected Light.*—In this instance the light which would pass through the well or aperture in the stage, is shut off by a diaphragm; or an opaque plate, either white or black, may be placed on the stage beneath the preparation. Light is then concentrated upon the upper surface of the object by means of the bull's-eye condenser. When artificial illumination is used, the plane surface of the condenser should be directed towards the object. Small silvered reflectors are sometimes employed instead of, or in conjunction with, the bull's-eye condenser, but they present no special advantages in ordinary work.

Sorby's modification of Beck's parabolic reflector is valuable for a certain class of observations; and descriptions of this, the Lieberkuhn, etc., will be found in some of the larger works relating to microscopical study.

(ii.) *Examination by ordinary Transmitted Light (or Substage Illumination).* In this case the light is reflected from the mirror, and passes through the aperture in the stage and through those parts of the preparation which are transparent or translucent. By this kind of illumination those coloured objects which transmit light should have their colours carefully noted by the observer, as the colours may at times partially serve to distinguish certain minerals. In some instances, as when the section is not very translucent, or the magnifying power is very high, the light will be found insufficient, and may be increased by the use of a condenser placed below the stage. Of such condensers there are many different patterns, of which that shown in Fig. 6 is one of the simplest, as by the temporary removal of the upper lens it will be found that the illumination of the section is greatly improved when the latter is in the focus of the condensing lens.

(iii.) *Examination by Parallel Polarized Transmitted Light.*

a. With the polarizer only.

This arrangement is used when the pleochroism of a mineral has to be determined. An explanation of the phenomena will be given later on.

b. With both polarizer and analyser.

- *α.* With the principal sections or shorter diameters of the Nicols parallel.
- *β.* With the principal sections of the Nicols crossed at right angles.

The latter is the condition under which the observer will generally have to work; and the accurate crossing of the Nicols is a matter of such great importance that the student should learn at once how to accomplish this necessary operation.

When the principal sections of the Nicols are parallel, light is transmitted, and the field of the microscope is brightly illuminated. When, however, they are crossed, the field remains dark. Let us assume that the maker of the microscope has not placed either of the Nicols accurately in position. Each Nicol is mounted in a piece of cork; and the cork cylinder, with its contained prism, will have to be turned within its brass fitting until it is exactly in the required position. To do this, two stout needles or pins may be employed, and they may be driven through a piece of wood at a suitable distance apart, so that the points of the needles can be simultaneously stuck into the cork on either side of the prism. The operator must, however, remember that these calcite prisms are very soft, and that an accidental slip of one of the needles may seriously injure, if not ruin, the prism. Another way is to push the cork containing the prism a little distance above the fitting, so that it can be turned by the fingers until properly adjusted; but in sliding the cork down again into its fitting there is considerable risk of altering the adjustment already made. Assuming, however, that a safe means of turning the corks has been found, the polarizer is brought into position beneath the aperture in the stage with its stop in one of the clicks, an objective is screwed on, and the A, or Nó. 1, eye-piece, with its spider lines, is inserted in its proper place. Light is now reflected from the mirror up the tube of the microscope, and a glass slip, on which a few hair-like crystals of a rhombic mineral such as mesotype are mounted, is placed on the stage, and one of the crystals is brought into focus. The eye-piece must of course be provided with a stop, so that it cannot be accidentally twisted round, and this insures the fixed position of the spider-lines. Now turn the stage of the microscope until the longest axis of the crystal coincides with, or is exactly parallel to, one of the spider-lines. Put on the analyser, and turn it slowly round. There will be four points during its complete rotation at which the field will attain its maximum darkness; and if, exactly at one of these points, the crystal of mesotype should become absolutely dark, and in fact disappear from view, the polarizer, at all events, will be in its proper position. But we have assumed that this was not so. Such being the case, we should find that at none of the points at which the field attained its maximum darkness did the crystal of mesotype become absolutely dark. We should see it still as a more or less illuminated rod. We must then turn the cork containing the polarizer in its fitting until, when restored to its stopped position (say 0°), and the field again brought to maximum darkness,—to do which it may be necessary to turn the polarizer slightly,—the crystal disappears completely in the gloom. The process of shifting the prism in its fitting is a very tedious one, apparently the most delicate touch often sufficing to put it completely out of position.

We may now infer that the polarizer is properly adjusted; namely, with its principal section exactly parallel to one of the spider-lines in the eye-piece. We have next to attend to the analyser.

If the polarizer be clicked at 0°, we now set the analyser, or at least its fitting with the index, exactly at 90°. The principal section of the prism should then be accurately at right angles to that of the polarizer. But we have assumed that the analyser is badly adjusted. When, therefore, we look through it, we see that the field is not at its maximum darkness; and when we turn the analyser, we shall see through how many degrees it travels before the maximum darkness supervenes. Again we have to go through the tedious process of twisting the cork and its contained prism, until at last (when the analyser is set at 90° and the polarizer at 0°, and when the mesotype crystal is exactly parallel to one of the spider-lines) all appears dark, both the field and the crystal being as dark as they can be. The Nicols are then accurately crossed. The reason why a mesotype, or other rhombic, crystal has been employed will be readily understood when the student has mastered a few of the following chapters.

2. PROPAGATION OF LIGHT, REFLECTION, REFRACTION, DOUBLE REFRACTION, OPTIC AXES, ETC.

Propagation of Light.—Books are not wanting in which the principles of optics are more or less clearly explained, and to these the reader should refer. (See Bibliography in Appendix.) For present purposes it will suffice to remind the student that a ray of light travels in a straight direction from any luminous point, and that it consists merely of a vibratory motion, communicated to one particle of ether, and transmitted from that particle to the next, so that from one disturbance a chain of disturbances ensue. These movements, or vibrations, take place at right angles to the direction in which the light-ray

FIG. 9.

travels, and constitute a succession of waves. Thus, in Fig. 9, *a e* represents the direction in which a ray of light is travelling, while the thick dots represent the arrest at any given moment of particles of ether in a state of vibration. It will be seen that they are thrown into a wave line through the successive vibration of the ether particles from the line of rest *a e* in directions at right angles to *a e*, and on either side of that line if the ray be polarized, or on all sides of it if it be a ray of ordinary light. In the figure, *a*, *c*, *d*, and *e* are nodal points, or points to which certain particles have returned once, or many millions of times, since the luminous vibration originated (*i.e.*, since the light was generated). They were the starting-points of the particles *a*, *c*, *d*, and *e*.

The point *b* was also the starting-point of the particle which has now reached *b′*. The distance *b* to *b′* is termed the *amplitude* of the vibration, and it is the full extent of the swing of this particle upon that side of the line. The particles, after returning to their starting points, pass to an equal distance on the other side of the line *a e*. In this way the wave is ever travelling onwards, while the particles merely swing backwards and forwards in the same paths at right angles to the direction in which the luminous wave travels. In Fig. 9, *a d* represents a wave-length usually denoted by λ; *a c* is half a wave-length, or $\frac{1}{2}\lambda$; *a b* a quarter wave-length, or $\frac{1}{4}\lambda$.

The wave-lengths are different for light of different colours, getting shorter and shorter as they succeed one another from the red to the violet end of the spectrum, the red rays having the longest waves and the least velocity, while the violet have the shortest waves and the greatest velocity, or rapidity of vibration, on either side of the line in which the ether particles originally rested. The time occupied in the performance of an entire vibration is termed the *period* of vibration.

The particles in different and in like positions at any given moment, as indicated by the dots in Fig. 9, are said to be in different or like *phases*, as the case may be; and it will be seen that a wave-length is the distance between any two particles which, at a given moment, are in the same phase of vibration, while there is a half wave-length between those in precisely opposite phases. The amplitude of a vibration is independent of the wave-length, so that it may vary for light of the same colour.

The amplitude determines the intensity of the light; the wave-length, its colour. Light of the same colour may be propagated with different velocities in different media, and consequently the wave-lengths may vary, but the period of vibration remains constant.

The velocity is dependent upon the elasticity of the medium through which the light travels, or the resistance which the particles of ether in the intermolecular spaces of that medium offer to any displacing force. The velocity consequently becomes less in proportion to the compactness of the body through which the light passes; and as in all crystals, except those of the cubic system, the elasticity is not equal in all directions, so in these crystals rays of light transmitted through them will vibrate with the same velocity in certain directions only. When two luminous waves of equal intensity (*i.e.*, with equal amplitude of vibration) travel in the same direction, and vibrate in the same plane, they will, if they differ in phase by half a wave length, or by any uneven number of half wave lengths, neutralize each other, and darkness will result.

In Fig. 10, the wave-line *a b* is just half a wave-length in advance of the wave line *c d;* and if we assume that they both vibrate in the plane of the paper, they will neutralize each other. Or we might express the same fact in a different

FIG. 10.

manner, as in Fig. 11, by saying that the particles *x* and *y* are in exactly opposite phases of vibration.

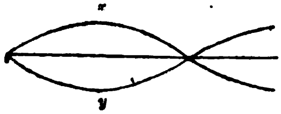

FIG. 11.

Another result of this principle of interference is, that when two luminous waves of equal length, but differing in amplitude or intensity, travel in the same direction and vibrate in the same plane and in the same direction, a wave will result the amplitude of which will be equal to the sum of the amplitudes of the two waves. This is indicated by the dotted line in Fig. 12. If, however, they vibrate in the same plane, but in opposite directions, the wave which results will be of diminished and not of increased amplitude, as indicated by the dotted line in Fig. 13.

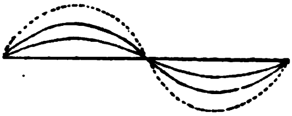

FIG. 12.

FIG. 13.

Reflection.—This consists in the bending back of a ray of light from the surface on which it impinges. The angle of incidence, or angle at which the ray falls on the reflecting surface, is equal to the angle of reflection. There is, however, a limiting angle for different substances, beyond which total reflection occurs.

Owing to the reflection of light from the faces of crystals, their angles can be most accurately measured by means of goniometers, the construction and methods of using which will be found fully described in various text-books of mineralogy. By the light reflected from certain naturally roughened, or from the faces of artificially etched crystals, peculiar crucial, stellate, and variously arranged markings or light-figures may often be discerned, the disposition of the markings corresponding with the symmetry of the crystal face.

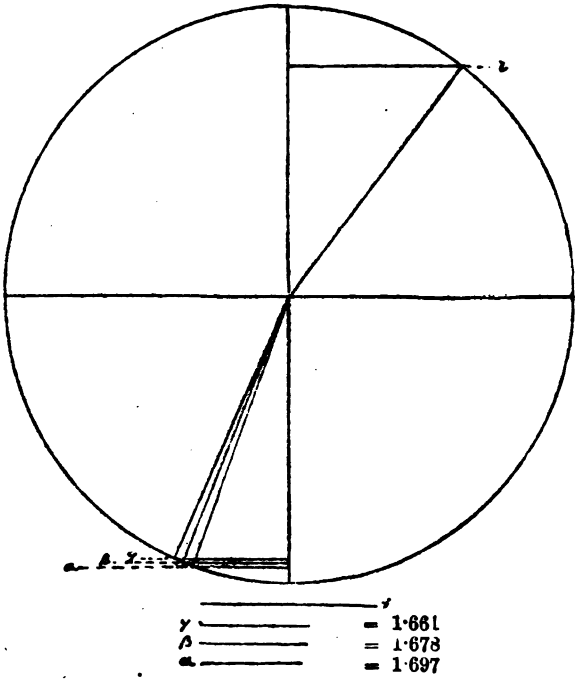

FIG. 14.

Refraction.—If a ray of light fall obliquely upon the surface of a medium of a density different from that through which it has already travelled, it will be refracted or bent from the course which it previously pursued; and if the passage be from a rarer to a denser medium, the refracted portion of the ray will be more or less inflected towards a line drawn at right angles to the limiting surface of the two media. The angle of incidence is the angle included between this normal and the incident ray, while that of refraction lies between the normal and the refracted ray.

The two following laws govern simple refraction. i. The sines of these angles bear a constant relation to one another for the same two media, which is termed the *index of refraction,* usually denoted by the letter *n*. ii. The incident and the refracted rays always lie in the same plane, which is perpendicular to the limiting surface between the two media.

The value of *n* may be procured by dividing the sine of the incident by that of the refracted ray. In optically uniaxial crystals there are two, in biaxial crystals there are three different refractive indices to be noted, namely, a maximum, a mean, and a minimum, respectively denoted by the letters α, β, and γ. In Fig. 14 the sines of the angles of maximum, minimum, and mean refraction in Olivine are diagrammatically represented side by side for comparison.* The relation of the refractive indices to the axes of optical elasticity, and to the velocities in a biaxial crystal are here given:—

Axes of Elasticity . . max. $= \mathfrak{a}$: mean. $= \mathfrak{b}$: min. $= \mathfrak{c}$
Refractive Indices . . min. $= \alpha$: mean. $= \beta$: max. $= \gamma$
Velocities . . . . . max. $= \frac{1}{\alpha}$: mean. $= \frac{1}{\beta}$: min. $= \frac{1}{\gamma}$

The determination of the index of refraction of a crystal may be effected in various ways, as by cutting a prism from the crystal and measuring first the refracting angle α by means of the goniometer, just as in the measurement of an ordinary crystal, and then determining the amount of minimum deviation-

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* α is the refractive index for rays propagated at right angles to $\mathfrak{a}$ and vibrating parallel to $\mathfrak{a}$. β for those propagated at right angles to $\mathfrak{b}$ and vibrating parallel to $\mathfrak{b}$. γ for those propagated at right angles to $\mathfrak{c}$ and vibrating parallel to $\mathfrak{c}$. The direction of greatest velocity corresponds with the index of least refraction and *vice versa,* or the velocities are inversely proportional to the refractive indices.

tion *d,* which occurs when the incident and emergent rays make equal angles with the faces of the prism. Then—

$$\frac{\sin \frac{1}{2}(a+d)}{\sin \frac{1}{2} a}=n.$$

Another method of determining the index of refraction consists in accurately focussing under the microscope an object, such as a delicately engraved line on a glass plate, and noting,—by means of the carefully-divided head of the fine adjustment, or by a divided scale, which moves with the tube of the microscope against a fixed vernier on the limb of the instrument,—the precise reading when the line is in focus. A flat plate of the mineral under investigation must now be procured, either by cleavage or by grinding and polishing. This plate is then laid upon the glass plate so as to cover the engraved line, and the microscope must be racked back in order to accurately re-focus the line *through* the plate of the mineral. This being done, the distance between the original and the present reading of the scale (*i.e.*, the distance racked back, *r*) must be noted. The thickness, *t*, of the mineral plate should then be accurately measured, and the value of *n* computed by the formula—

$$\frac{t}{t-r}=n.$$

This is commonly known as the Duc de Chalune's method, and dates as far back as 1767.

The total-reflectometer is an instrument also used for determining indices of refraction; and descriptions of its construction and use will be found in some of the larger text-books of mineralogy and crystallography.

It should be noted that the borders of transparent bodies appear more or less dark when surrounded by a strongly refracting medium, the darkness being greater in proportion to the difference in the respective indices of refraction of the enveloped and the enveloping substances. The wrinkled or roughened-looking surfaces of sections of olivine crystals owe the strongly-marked appearance of these irregularities to the high index of refraction of the mineral.

Double Refraction.—Iceland spar, the most transparent variety of calcite, is the mineral which affords the readiest means of studying this property. It cleaves easily into rhombohedral forms; and if we place a moderately thick cleavage rhombohedron with one of its faces flat upon a piece of paper on which a small ink-spot has been made, we shall see two images of the spot, one being rather fainter than the other. If, instead of the paper and ink-spot, we employ a piece of card through which a small pin-hole has been made, and hold the spar before the eye with the perforated card behind it, we shall see that the light which passes through the pin-hole traverses the spar in two directions, and gives rise to two luminous images of the hole, one of which is rather less brightly illuminated than the other.

In either case, the ray of light, on entering the spar, is split into two rays, one of which,—namely the more refracted,—is termed the *ordinary*, while the other is termed the *extraordinary ray*. If in either experiment we turn the spar slowly round, keeping it flat against the dotted paper or the perforated card, we shall see that one image travels round the other, the stationary one being that which is formed by the ordinary ray. The ordinary and extraordinary rays are, for the sake of brevity, respectively symbolized by the letters *o* and *e* (Fig. 15). The ordinary ray obeys the laws of simple refraction, the extraordinary ray does not do so.

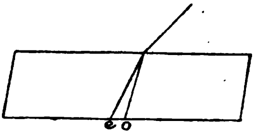

FIG. 15.

If we take a similar cleavage rhombohedron of Iceland spar, and grind away the poles, we shall form two triangular faces, of which *a a* and *b b* (Fig. 16) represent the traces. Having polished these triangular planes, place the spar with one of them flat upon the paper and over the ink-dot. On looking straight down upon the dot,—*i.e.*, in a direction normal to the parallel triangular planes,—only a single image of the dot will now be seen; but if we look obliquely, the two images will again become visible. The direction in which the single image of the dot is seen, is that in which no separation of the rays takes place. It is a *direction* of no double refraction, and is termed the *optic axis* of the mineral. Those crystals which belong to the hexagonal and tetragonal systems have, as in the preceding instance, but one optic axis, and they are consequently known as *uniaxial* crystals. In some of them, however, the ordinary is less refracted than the extraordinary ray. In this case they are said to be *positive*, while those in which the ordinary ray is the more refracted, as in Iceland spar, are said to be *negative* uniaxial crystals. If, for instance, in Fig. 15 we transpose the letters *o* and *e*, we shall have a diagram of a positive uniaxial crystal; but, as the figure stands, it represents a negative one.

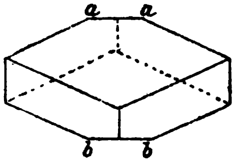

Fig. 16.

In all of these uniaxial crystals the direction of the optic axis coincides with, or is parallel to, the principal crystallographic axis. The optic axis should not be pictured as a single line passing through a crystal, but as a direction, which might be rendered diagrammatically by an infinite number of parallel lines traversing the crystal in the direction of the principal crystallographic axis. The interference figure, described on p. 61, which is seen when a parallel-faced slice of a uniaxial crystal is cut normal to the principal crystallographic axis, is not merely visible at one spot in the plate, but is also seen in any like direction when the plate is moved about upon the stage of the polariscope.

The indices of refraction for *o* and *e* differ in different minerals. For the same mineral the separation of the two images depends, of course, upon the thickness of the plate employed. Thus, two cleavage rhombohedra of calcite, of equal thickness, placed one above the other in a similar position, will give twice as great a separation of the images as either of them would give singly.

3. Polarization of Light.

When a ray of light is compelled to perform its vibrations *in one plane only,* it is said to be polarized. (This is also termed plane polarization, or parallel polarization, as distinguished from circular polarization.) A ray of ordinary light performs its vibrations in all directions at right angles to that in which it travels. If such a ray (*i i*, Fig. 17) be reflected from a horizontal plate of glass,[*] G, in the direction of the line *i p*, certain peculiarities will be noted if the reflected ray be examined through a plate of tourmaline cut parallel to the principal axis. When the tourmaline is held with its principal axis in the direction of the plane P P P (which is termed the plane of

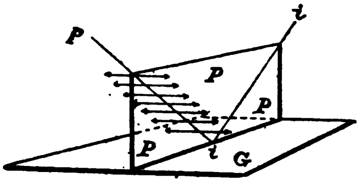

Fig. 17.

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[*] The angle at which complete polarization of the reflected ray takes place is 58° for glass. This is termed the *polarizing angle* for glass. For substances with higher or lower refractive indices than glass, this angle is proportionately higher or lower. At the polarizing angle, the refracted and reflected rays form a right angle.

polarization, and in this instance is vertical), no light will be transmitted through the tourmaline; but if the principal axis be placed horizontally, light then passes through. In the former instance we have conditions similar to those which exist in the case of crossed Nicols (see p. 27); in the latter, the conditions are such as occur when the Nicols are parallel.

We have already had to mention Nicol's prisms; and, as they afford the most convenient and important means of polarizing light and of analysing the polarized ray, their construction may be briefly explained. A Nicol's prism consists of a cleavage prism of Iceland spar, of which the two end cleavage faces are inclined 71° to the long edges of the prism. These end faces are, however, ground down and polished so that they lie at 68° to the long edges. The prism is then sliced in halves along a plane lying at right angles to the principal section, and passing through the obtuse angles *b b′* (Fig. 18, *A*); and the cut faces, after having been polished, are cemented together by Canada balsam. A ray of light, *i i′*, on entering the prism, is split into an ordinary and an extraordinary ray. The extraordinary ray vibrates in a plane which contains the incident ray and the optic axis; *i.e.*, in the principal section. The ordinary ray vibrates in a plane at right angles to that of the extraordinary ray. Of these the latter—*i e*, Fig. 18 ($n = 1·536$)—passes through the prism with scarcely any deflection, as it has almost the same refractive index as the balsam; but the ordinary ray, *i o*, has a higher refractive index ($n = 1·654$), and undergoes *total reflection* from the surface of the balsam in the direction *o o*, Fig. 18, *A*. A transverse section of the prism is shown in Fig. 18, *B*; its shorter diameter, *s s*, indicating the position of the principal section, which in Fig. 18 *A* is represented by the plane of the paper.

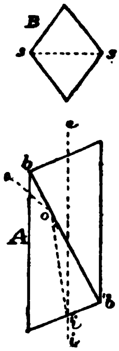

Fig. 18.

The method of constructing such prisms has, however, been modified in various ways both in the manner in which the prism is sliced, and also in the nature of the cementing medium. By these means the length of the prism is considerably diminished.

Such a prism serves either as a polarizer or as an analyser; for the two rays which traverse a crystal of Iceland spar, or indeed any doubly-refracting crystal, are polarized, the plane of vibration of the ordinary being always at right angles to that of the extraordinary ray. Since in a Nicol's prism the ordinary ray is abolished by total reflection, only one set of vibrations are transmitted, namely, those parallel to the principal section or shorter diameter of the Nicol. When the principal sections of the analysing and polarizing Nicols are parallel, light is transmitted; when they are crossed, the field is darkened. The method of accurately crossing the Nicols has already been explained (p. 27).

Why darkness is produced by crossing the Nicols.—The light which is transmitted by a Nicol's prism vibrates only in the principal section; and, consequently, when the principal sections of the polarizer and analyser are accurately crossed, none of the light transmitted by the polarizer can pass through the analyser. The darkness which results is not due to any interference; for interference can only take place in the case of rays which differ in phase by a half or an odd number of half wave-lengths, and which *vibrate in the same plane;* and that the darkness is, therefore, not owing to interference, is proved when the principal sections of the Nicols are placed parallel, for, under these circumstances, light is transmitted. The darkness produced by crossed Nicols is simply due to the extraordinary ray from the polarizer vibrating, when it enters the analyser, in the direction that an ordinary ray would do, so that it undergoes total reflection.

Colours visible when Doubly-refracting Crystals are viewed in Polarized Light.—When, between crossed Nicols, we insert a thick plate of a colourless, doubly-refracting mineral, the field of the microscope or polariscope no longer remains dark. Light is transmitted, but no colours are visible. If, however, we take a considerably thinner plate, or a mere film of the same mineral, and again examine it between crossed Nicols, we shall see that the plate or film* exhibits more or less brilliant colour. If it be a plate with perfectly parallel and smooth faces, the colour will probably be uniform. If, however, the plate be of irregular surface, with possibly some adhering films, it will appear variously coloured. If, instead of a parallel-faced plate, we cut the mineral into a thin wedge, colours will appear in bands parallel to the thin end of the wedge. We have now to consider the cause of these colours. They depend upon the retardation of certain rays of light. A polarized ray which enters the plate of the crystal under examination, is split into an ordinary and an extraordinary ray, both of which are polarized, but one vibrates in a plane at right angles to the other. These two rays traverse the crystal with a somewhat different length of path, and with somewhat different velocities, since one of them will travel nearer to an axis of greater or less elasticity in uniaxial crystals, or to an axis of greatest, mean, or least elasticity in biaxial crystals, than the other. The *index of refraction* of the mineral and also the *thickness* of the plate have a very material influence on the retardation of one or other, or in different degrees upon both of the rays, so that one of them leaves the plate in a more or less different phase from the other. The direction in which the plate is cut with reference to an optic axis also affects the colour. So far no interference results, since the two rays are vibrating in planes at right angles to one another. On entering the analyser, however, each of these rays is again split into two rays, one ray in each pair vibrating in parallel planes, while the two residual rays vibrate at right angles to them. In a given position (say with the Nicols crossed), two of the rays undergo total reflection in the analyser, and two only are transmitted; but these differ in phase, and are consequently in a condition which admits of interference. This ensues, but only affects rays which have a certain wave length, the residual colours produced by wave lengths other than those extinguished, being transmitted. For instance, in a tolerably thick plate we may get extinction of the red rays by interference. The red rays have longer wave-lengths than those of other colours, and the residual colours will then be transmitted. On the other hand, when the shorter waves are extinguished, the longer ones, or those nearer the red end of the spectrum, are transmitted. When the directions of vibration in the crystal lie at an angle of 45° to the principal sections of the crossed Nicols, we have the strongest chromatic effects,* but, as the crystal is rotated on the stage, they become less brilliant, until they merge into darkness, and at this point an axis of elasticity, *i.e.*, a direction of maximum extinction, is parallel to the principal section of one of the Nicols.

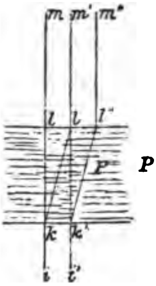

FIG. 19.

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* The strength of the double refraction, in plates of uniform thickness, but of different minerals, *i.e.*, the *difference* which may exist between the refractive indices of the rays, directly affects the colours seen in polarized light. With weak double refraction, the colours will be those low down in Newton's scale; with strong double refraction, the colours will be those of higher orders. (*See* Newton's Colour Scale, p. 95.)

The difference of phase which results from retardation in a plate of a doubly-refracting crystal, will be better understood by referring to fig. 19, where *i k*, *i′ k′* represent two plane polarized rays, each of which, on entering the doubly-refracting plate P, is split into two rays. The ray *k l′* has a longer path than the ray *k′ l′*, so that, when they emerge from the plate, they have a difference of phase; the waves of *k′ l′* being a certain distance in advance of those of *k l′*. The two waves then travel together in the direction *l′ m′*, but as they are polarized in planes at right angles to one another, they cannot interfere and produce colour until their vibrations are brought into the same plane by the analyser.

The differences in colour displayed by crystals when they are viewed in polarized light, often afford important information regarding their structure. Pseudomorphs, for instance, may be frequently recognised by this means. Thus we may sometimes meet with a crystal in a rock-section, which in ordinary transmitted light shows no structural peculiarity; yet, when examined in polarized light, we find it to be made up of many crystals, which, owing to the different positions in which their optic axes lie, or, in other words, to their different optical orientation, present a more or less mosaic-like appearance.

Again, as we shall frequently have occasion to notice, the types upon which crystals are twinned may often be ascertained by means of the differently coloured areas which the sections of crystals exhibit in plane polarized light. A colourless triclinic felspar will, for example, appear banded with numerous coloured bars, which may indicate twinning upon the brachy-pinacoid or upon the basal plane.

4. AXES OF OPTICAL ELASTICITY, EXAMINATION IN POLARIZED LIGHT.

Crystallographic Axes.—These are imaginary lines of infinite length, around which the molecules of a crystal are assumed to be built together in accordance with definite laws. The general principles of crystallography are sufficiently explained in text-books of Mineralogy, and it is therefore needless to recapitulate them here. It may, however, be well to remind the beginner that the crystallographic axes are usually symbolized by letters; and that in the following pages the front-and-back axis is denoted by *a*, the right-and-left axis by *b*, and the vertical axis by *c*.

In reading crystals of the hexagonal and tetragonal systems, the principal axis is set vertically. In all directions around this axis, and at right angles to it, the crystals are endowed with similar properties.

Crystals of the rhombic system are assumed to be so placed that the brachydiagonal corresponds with the axis *a*, and the macrodiagonal with *b*.

In those of the monoclinic system, the inclined axis is assumed to slope upwards and away from the observer, so that it is taken as the axis *a*, while the orthodiagonal corresponds with the axis *b*.

In the triclinic system the brachydiagonal corresponds with the axis *a*, and the macrodiagonal with *b*.

In all of these systems *c* stands for the vertical axis.

Axes of Optical Elasticity. — In uniaxial crystals an optic axis is a direction in which light undergoes no double refraction or polarization, and travels with a single velocity; but, in the case of an axis of optical elasticity, two rays, polarized in planes at right angles to one another, travel in the same direction and with different velocities. In the case of a uniaxial crystal, one axis of optical elasticity coincides with the optic axis, and the characters which distinguish it from an optic axis become abolished, since, in nearing this direction, the difference in velocity of the two rays becomes less and less, until, in the actual direction of the optic axis, where their velocities would be the same, they merge into one ray.

In the case of a transparent crystal, in which an axis of optical elasticity is normal to a pair of opposite and parallel faces, or in any parallel-faced plate cut from a doubly-refracting crystal in such a manner that the faces are normal to an axis of elasticity, we shall find, if we look at an ink-dot in a direction at right angles to the faces of the plate, that only a single image of the dot is visible, the phenomenon being precisely the same as if we were looking through a plate cut at right angles to an optic axis. If, however, the faces of the plate be not parallel, we shall, on looking in the direction of the axis of elasticity, see a double image. The vibrations of the two rays, after travelling in the direction of an axis of elasticity, emerge with a difference of phase ; and in this respect an axis of elasticity differs from an optic axis.

In optically uniaxial crystals the principal crystallographic axis, which is also the optic axis, is likewise an axis of greater or lesser optical elasticity, while any line lying in a plane at right angles to this axis is also an axis of optical elasticity. There are therefore in uniaxial crystals two elasticities, a greater and a lesser.

In optically biaxial crystals there are three axes of elasticity; viz., greatest, mean, and least, respectively symbolized by the letters $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$. These must not be confounded with the italic letters a, b, c, used to denote the crystallographic axes; for, although $\mathfrak{a}$ may sometimes be parallel to or coincide with a, $\mathfrak{b}$ with b, and $\mathfrak{c}$ with c, yet this is by no means invariably the case. Thus, for instance, in crystals of olivine, we have $a=\mathfrak{c}$, $b=\mathfrak{a}$, $c=\mathfrak{b}$.

The axes of optical elasticity are also directions of maximum extinction, or those directions in which a crystal transmits no light when viewed between crossed Nicols. The axes of elasticity *always lie at right angles to one another*, and the two rays which travel together along such an axis are polarized at right angles to one another. In determining the optical properties of a crystal, it is most important to ascertain the precise position of the axes of elasticity, with reference to the crystallographic axes or to known crystallographic edges which lie parallel to the corresponding crystallographic axes.

The methods employed to effect this object are various. The most simple, perhaps, is that described on page 28, as affording a convenient means of accurately crossing the principal sections of the Nicol's prisms.

Assuming the Nicols to be accurately crossed, a section of the crystal under investigation is brought into the field of the microscope, and adjusted so that one of its edges (and it must be an edge which is known to be parallel to a crystallographic axis) is coincident with one of the crossed spider-lines in the eye-piece. Due precaution must, of course, be taken to ascertain that these spider-lines are respectively and exactly parallel to the principal sections of the accurately-crossed polarizer and analyser.

The observer will now see one of two things—either that the crystal is in perfect obscurity, or else that it is more or less illuminated. If the former, then the edge of the crystal, also the corresponding crystallographic axis, is precisely parallel to one of the directions of maximum extinction of light, *i.e.*, to one of the axes of optical elasticity. If, however, the crystal be illuminated, no matter how slightly, it is evident that no axis of elasticity is precisely parallel to the edge coinciding with the spider-line. The position of the stage of the microscope should then be carefully noted by means of its divided circle, after which it should be slowly turned until the maximum darkness is attained by the crystal. There may at first be some difficulty in fixing this exact position; and the observer will find that it is easy for him to make an error of two or three degrees. By repeated trials, however, he will get an approximately true result. Where great accuracy is needed, it is best to take the mean of many careful observations.

A plate of quartz, commonly known as "Klein's plate," is sometimes employed for this purpose. It is inserted in a slot situated a little above the objective; and in consequence of the particular thickness of the quartz, the field becomes coloured. The analyser should next be turned until a neutral tint, just between violet and red, pervades the field—*teinte sensible.* The known edge of the crystal now being parallel with one of the spider-lines, it will be seen whether the crystal appears of exactly the same tint as the field. If not, the position of the stage must be noted, and it should then be turned until the crystal is of precisely the same tint as the field. The reading of the stage is again taken, when the number of degrees through which it has been moved will denote the angle which an axis of elasticity makes with the known crystallographic edge, *i.e.*, with a known crystallographic axis.

The foregoing are, however, inferior in precision to other methods now adopted. These are of a stauroscopic character. The simplest, but least accurate, consists in placing a plate of calcite, cut at right angles to the optic axis, immediately above the eye-glass of the eye-piece, and just beneath the eye-piece analyser. The crystal is arranged as in the previous cases. On looking through the instrument, a series of coloured rings will now be seen, traversed by a dark cross, the arms of which correspond with the principal sections of the crossed Nicols. If there be perfect coincidence of an axis of elasticity with the known edge of the crystal, the interference figure of the calcite plate will remain undisturbed; but if there be any deviation of the axis of elasticity from the direction of the edge of the crystal, the cross will be more or less distorted, and the stage must be turned until the cross is properly restored. In this method there is also a tolerably wide margin for error.

Brezina's and Calderon's composite calcite plates afford much greater accuracy; but the most perfect arrangement yet devised for this purpose is Bertrand's stauroscope eye-piece. This consists of four plates of quartz, two of which turn the plane of polarization to the right, while the two others turn it to the left hand. These right- and left-handed quartzes are arranged alternately, and are carefully cemented together, so that their planes of junction intersect at right angles. Being all of the same thickness, they impart a uniform tint to the field, so that a crystal placed with a known edge parallel to one of the junction lines appears of the same tint as the field if an axis of elasticity be parallel to that edge. If not, the crystal, which should lie beneath the intersection of the crossed junction lines, will appear differently tinted in the alternate quadrants.

A reading is then taken, and the stage is turned until uniformity of tint is restored, the angle through which the stage has been turned being the angle between the axis of elasticity and the known edge, or its corresponding crystallographic axis.

Beginning with those biaxial crystals which possess the lowest grade of symmetry, we find that—

In the Triclinic system the directions of maximum extinction, or the axes of optical elasticity, do not correspond in direction with any of the crystallographic axes.

In the Monoclinic system there is only one axis of elasticity which corresponds with a crystallographic axis, and that is the orthodiagonal, so that we may picture the three axes of elasticity in a monoclinic crystal as three straight wires, intersecting at right angles, the wire corresponding with the orthodiagonal serving as an axle about which the two others may be turned, so that they may occupy any position with reference to the vertical and clinodiagonal crystallographic axes. Although their position is variable in the monoclinic system, these axes of elasticity have definite positions in the different minerals which crystallize in that system.

In the Rhombic system the three axes of elasticity coincide with, or are parallel to, the three crystallographic axes. It is for this reason that a rhombic crystal is best suited for ascertaining whether the Nicol's prisms in the polariscope are accurately crossed. (See p. 28.)

Although uniaxial crystals, when cut at right angles to the optic axis, appear dark in parallel polarized light during rotation between crossed Nicols, yet sections of biaxial crystals at right angles to an optic axis, transmit light under these conditions. The reason of this is, that in biaxial crystals, neither of the optic axes coincide with, or are parallel to, an axis of symmetry, and they consequently undergo dispersion, so that, as Rosenbusch remarks, there can be no section, strictly speaking, at right angles to an optic axis for light of two different colours. Even when monochromatic light is employed, the section is also illuminated when rotated between crossed Nicols, since, owing to internal conical refraction (p. 58) around the direction of the optic axes in biaxial crystals, rays of light travelling in these directions become separated into an infinite number of rays, which, forming the surface of a cone, are polarized in all directions.

Among the optically uniaxial crystals we find that—

In both the Tetragonal and Hexagonal systems the directions of maximum extinction are parallel to the edges of any of the prisms in either system; while in both systems sections, taken at right angles to the principal crystallographic, or optic, axis, remain dark between crossed Nicols during a complete revolution of the stage.

Crystals of the Cubic system, no matter in what directions they may be cut, transmit no light when viewed between crossed Nicols, but remain dark in all positions, unless they have been strained by pressure, or are in an abnormal condition of tension, in which cases they exhibit more or less double refraction; and what is here said of cubic crystals applies equally to amorphous substances. A plate of rock-salt, for instance, displays no double refraction, nor does a plate of glass, unless in a condition of strain or tension. Good examples of tension may occasionally be met with in the natural glass, or vitreous lava, known as obsidian. It is also well seen in the mineral hyalite, or Muller's glass, an opaline form of silica.

Amorphous minerals and those crystallizing in the cubic system are said to be *isotropic*, since their optical properties are the same in all directions.

Crystals of the cubic system which have been formed at a widely different temperature from that which they subsequently attained on cooling, also show abnormal properties of double refraction; but their double refraction has, in some cases, been found to be abolished by raising them to the temperature at which they originally crystallized.

The crystals of the other five systems are said to be *anisotropic*, since their optical properties are not uniform in all directions. Among the anisotropic crystals the phenomena of extinction, already alluded to, may be separated into two classes—

(*a*) *Parallel* or *straight* extinctions, in which the directions of maximum extinction are parallel to those crystallographic edges which correspond with certain crystallographic axes; and—

(*b*) *Inclined* or *oblique* extinctions, or those which are inclined at certain angles to crystallographic axes, or the edges which correspond with them.

We may therefore summarize the extinctions of the anisotropic crystals in the following manner:—

Triclinic System.—All extinctions oblique.

Monoclinic System.—Oblique extinction in sections parallel to the clinopinacoids, or plane of symmetry. Parallel extinctions in sections parallel to the orthopinacoids and basal planes.

Rhombic System.—Parallel extinctions in sections parallel to the macropinacoids, brachypinacoids, and basal planes.

Tetragonal and Hexagonal Systems.—Parallel extinctions in sections parallel to the principal crystallographic axis (optic axis). Extinction in all azimuths in sections at right angles to this axis.

5. WAVE SURFACES.

Wave Surfaces in Uniaxial Crystals.—Luminous wave-surfaces are theoretically deduced from the velocity with which light is transmitted in different directions through crystals. To construct a wave-surface, we must imagine a luminous point situated within the crystal. In a crystal belonging to the cubic system, light is transmitted with equal velocity in all directions. If, therefore, we conceive a luminous point within such a crystal, the light emanating from that point, if its progress could be suddenly arrested, would be found to have travelled an equal distance from that point in all directions; and by joining these points of arrest, infinite in number, we should produce a *spherical* film, or luminous wave-surface.

The wave-surfaces in systems other than the cubic are not spheres; and we shall find that they are not so, because the molecular structure of the crystals belonging to these systems, as denoted by their parametral relations, is not uniform in all directions. Again, we shall find that the wave-surfaces of uniaxial differ from those of biaxial crystals; and this difference may be attributed to the uniformity in molecular structure around the principal axis of a uniaxial crystal, while no such uniformity exists in the molecular architecture of crystals belonging to the rhombic, monoclinic, and triclinic systems. If we could suddenly arrest the light emanating from a point within a negative uniaxial crystal, one of calcite for example, we should find that, during a given fraction of a second, light had travelled with different velocities for the ordinary and for the extraordinary rays; the former having travelled further in all directions around the optic axis of the crystal, while in the direction of the optic axis the two rays had journeyed together with the same velocity. In this direction the extraordinary ray has its least velocity. As for the ordinary ray, its velocity in the calcspar is constant, and its wave-surface is consequently a sphere; and, if we join up the points at which the extraordinary rays would be arrested, we should find the wave-surface to be an oblate ellipsoid of rotation, touching the spherical wave-surface of the ordinary ray in two points, *a*, *a*, Fig. 20, which are the poles of the optic axis, while in any section containing this axis the major axis of the ellipse for the extraordinary ray will be found to lie at right angles to the optic axis.

In intermediate directions, the velocity for the extraordinary ray becomes less and less, until it attains its minimum velocity, or that of the ordinary ray.

In Fig. 20, the circle *o o* represents the circular section of the spherical wave-surface for the ordinary ray, while *e e* shows the elliptical section of the oblate ellipsoid for the extraordinary ray in a negative uniaxial crystal.

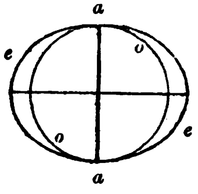

FIG. 20.

In a positive uniaxial crystal (*e.g.*, quartz), the wave-surface for the ordinary ray is also a sphere, while that for the extraordinary ray is a prolate ellipsoid, lying within the sphere and touching it at two points which are the poles of the optic axis. In this case the extraordinary ray has its greatest velocity in the direction of the optic axis, and its least velocity in a direction at right angles to it.

In Fig. 21, a section through these wave-surfaces is given,

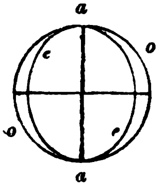

Fig. 21.

the letters *o* and *e* again indicating the wave-surfaces for the ordinary and extraordinary rays respectively.

By drawing lines radiating from a central point, the student will clearly realize that these lines represent, by their lengths between the central point and the points where they are cut by the ellipses, the corresponding velocities for the extraordinary ray, while as radii of the circles they denote the uniform velocity of the ordinary ray in each case.

Wave Surfaces in Biaxial Crystals.—These, like the wave-surfaces in uniaxial crystals, depend for their construction on the different velocities with which light is propagated within the crystals. In biaxial crystals there are three axes of optical elasticity: viz., maximum 𝔞, mean 𝔟, and minimum 𝔠. In biaxial crystals light is also propagated with a maximum velocity in one direction, a minimum in another, and a mean velocity in a third; while in the uniaxial crystals there are only two different velocities.

If, in a biaxial crystal, we first take the case of the plane which contains the axes of elasticity 𝔞 and 𝔟, a luminous ray travelling in the direction of the axis of elasticity 𝔞 is split into two rays, polarized at right angles to one another, one vibrating in the plane of the axis of mean elasticity 𝔟, while the other vibrates parallel to the axis 𝔠 of least elasticity. The vibrations parallel to 𝔟 have a mean velocity, and we accordingly mark off on the axis 𝔞 two points, one on each side of the origin or point of intersection of the axes 𝔞 and 𝔟, to represent this mean velocity. The vibrations parallel to 𝔠 have a minimum velocity, and we consequently mark off once more upon the axis 𝔞, on each side of the origin, two more points, the distances from the origin to these points being proportionately less than those previously marked off and representing the least or minimum velocity. We next consider the case of a ray of light travelling in the direction of the axis 𝔟. Here the two sets of vibrations are respectively parallel to the axes 𝔞 and 𝔠. Along the direction of the former we have the greatest velocity, while parallel to the latter we have the least velocity. We accordingly mark off distances from the origin upon the axis 𝔟, in one case proportional to the maximum, in the other to the minimum, velocity.

For directions lying between the axes 𝔞 and 𝔟, but in the same plane, we get a series of different velocities, and we measure off distances proportional to those which luminous rays will attain within the given time which is assumed to elapse between the commencement of the luminous vibrations and their arrest. If we now join up all of these points, we shall get a circle lying within an ellipse, as indicated in Fig. 22.

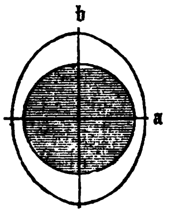

Fig. 22.

We next take the case of the plane in which the axes of elasticity 𝔟 and 𝔠 lie. Light travelling in the direction of the axis 𝔠 will vibrate in two directions, namely, in the direction of the axis 𝔞, and also in that of the axis 𝔟. Upon the axis 𝔠, therefore, we plot distances respectively proportional to the greatest and mean velocities, while upon the axis 𝔟 we again mark off distances from the origin respectively proportional to the maximum and minimum velocities. On joining up these and intermediate points of arrest of the luminous rays, we procure an ellipse lying within a circle, Fig. 23. Finally, we take the plane in which the axes 𝔞 and 𝔠 lie, and by adopting the same method of construction we arrive at a circle intersected by an ellipse (Fig. 24). The two lines *o o*, *o′o′*, which join the four points in which the circle cuts the ellipse, and which intersect in the centre of the figure, are *directions* in which the velocities are equal, and along these directions there is consequently no double refraction. These may be

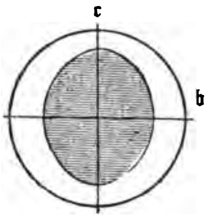

Fig. 23.

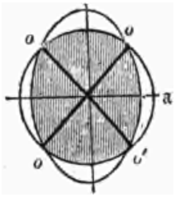

Fig. 24.

termed the two *optic axes*, or the secondary optic axes (see p. 58),* and they always lie in the plane which contains the axes a and c. By combining the three sections, namely—

That containing the axes of elasticity a and b,
" " " " b and c,
and " " " " a and c,

the complete wave-surface of a biaxial crystal may be constructed. If this be accurately done, it will be found that around the points *o o*, *o′o′*, Fig. 24, there are slight depressions, so that a plane applied to a model of the wave-surface will be in contact with it at all points around the pit or depression, the actual line of contact being a circle. The line *t t* (Fig. 26) indicates the trace of such a plane resting tangentially upon the circular and elliptical portions of the section figured.† It will be seen that the entire wave-surface of the crystal consists of two intersecting sheets, the one a sphere, the other an ellipsoid, and that they mutually intersect in the points *o o o′ o′*. Any one of these points *o* or *o′* is common to the curves both of the circle and the ellipse, so that rays passing in the directions *o o* or *o′o′* (Fig. 24) will

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* The student must not imagine that these optic axes are merely two fixed lines within the crystal. They may be represented by two lines; but an infinite number of lines parallel to them may be drawn within the crystal, of which each pair represents the optic axes. Fig. 25 may help to elucidate this matter. Here *o o*, *o o*, represent the optic axes, and the dotted lines a and c the bisectrices; but the lines marked *o′ o″ o‴* are also the optic axes, and a′, a″, a‴; c′, c″, etc., are also the bisectrices. The shading indicates portions of the crystal cut away.

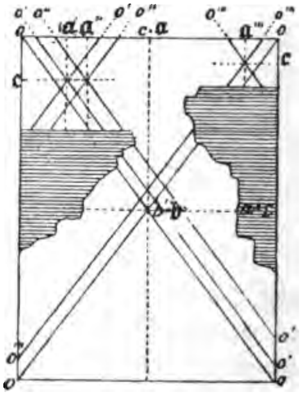

Fig. 25.

† Plaster models of the wave-surfaces of uniaxial and biaxial crystals are prepared by Dr. L. Brill, of Darmstadt.

travel with the same velocity. But, owing to the different curvatures of the surfaces of the sphere and the ellipse, the plane wave-surfaces or wave-fronts of the two rays will respectively be represented by the tangent planes, whose traces are indicated by the dotted lines *m m* and *n n*, Fig. 26 (which shows one quarter of a section of the entire wave-surface); and these tangents are not similarly inclined to the line O*o*. The tangent *t t* (Fig. 26) is, however, common to both, so that, if from the circular line of contact $x\,x_{\prime}$, which the tangent-plane makes with the two sheets of the wave-surface, lines be drawn to the point O in which *o o* and *o′o′* intersect, we shall get a cone, —or, in the entire figure, four cones,—whose apices are at O, while their bases are represented by the circular areas within the line of contact of the four tangent-planes. All those rays, therefore, which are propagated in directions normal to these common tangent-planes, or circular sections of the ellipsoid, will travel with the same velocity and will emerge as a cylinder *c c* in a direction at right angles to the common tangent-plane *t t*. Ox O$x_{\prime}$, are sometimes termed the axes of external conical

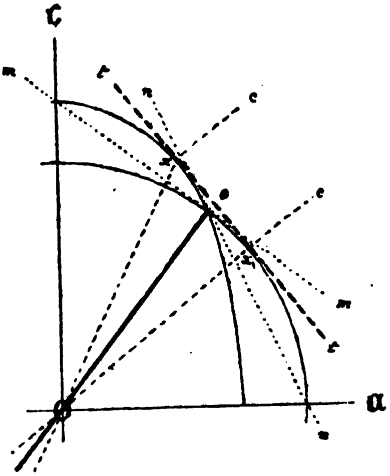

Fig. 26.

refraction. Of these, Ox, is the normal to the wave-front $t\ t$, and is one of the optic axes, a ray of light undergoing no double refraction in this direction. The divergence of the axes of external conical refraction from $O\ o$ is usually very slight and, correctly-speaking, $O\ o$ is one of the axes of internal conical refraction, or so-called secondary optic axes.*

6. BISECTRICES AND OPTIC NORMAL.

Bisectrices.—The optic axes in biaxial crystals are always symmetrically situated with reference to the axes of elasticity, or directions of maximum extinction. The plane which contains the two optic axes, known as the *plane of the optic axes*, or the *optic axial plane*, invariably contains also the axes of greatest and least elasticity. The angles formed by the crossing of the optic axes are alternately acute and obtuse; and the acute pair of angles is bisected by one of these axes of elasticity, which is known as the *acute bisectrix*, or *1st median line;* while the obtuse pair of angles is bisected by the other axis of elasticity, and is termed the *obtuse bisectrix*, or *2nd median line*. When merely the unqualified term *bisectrix* is used, it always implies the acute bisectrix.

The acute bisectrix is sometimes the axis of greatest, at others that of least elasticity. In the former case the crystal is said to be *negative*, in the latter, *positive*.

When the acute bisectrix is the axis of greatest, the obtuse bisectrix is that of least elasticity, and *vice versâ*.†

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* For a detailed account of conical refraction, see Groth's "Physikalische Krystallographie," 2nd ed.; Rosenbusch's "Mikroskopische Physiographie," vol. i., pp. 94 *et seq.*, 2nd ed.; Glazebrook's "Physical Optics," etc.

† In biaxial crystals the axis of least elasticity is sometimes called the *positive bisectrix*, and that of greatest elasticity, the *negative bisectrix*. When the positive bisectrix is the acute bisectrix, the double refraction of the crystal is positive, and when the negative is the acute bisectrix, the double refraction is negative.

In the triclinic system, there is no necessary relation between the bisectrices and the crystallographic axes.

In the monoclinic system a bisectrix is sometimes parallel to the orthodiagonal. (See horizontal and crossed dispersion, p. 80 *et seq.*)

In the rhombic system, they each coincide with or are parallel to a crystallographic axis.

Optic Normal.—The axis of mean elasticity in a biaxial crystal is never a bisectrix. It always lies at right angles to the plane of the optic axes, and is known as the *optic normal.*

The angle at which the optic axes intersect varies in different minerals, and sometimes, to a considerable extent, in the same mineral species; but the positions of the bisectrices are constant, and their determination is therefore a matter of great importance.

The method of ascertaining the positions of the axes of elasticity, has already been described on p. 46, *et seq.* The means of distinguishing which is the axis of greatest, and which that of least elasticity, *i.e.*, which is the acute, and which the obtuse bisectrix, will be given later on.

7. EXAMINATION IN CONVERGENT POLARIZED LIGHT.

The most simple appliance for examining sections of crystals in convergent polarized light, is the tourmaline pincette, or tongs. This consists of two plates of tourmaline, cut parallel to the principal axis. These are mounted in corks, which are inserted in circular collars, with a groove on the edge. A piece of stout wire is twisted so as to form the spring of the tongs, and each extremity of the wire is coiled round the groove on the edge of each collar, so that the discs carrying the tourmalines can be rotated. To use the instrument, the axes of the tourmalines are set either in a crossed or in a parallel position, the tongs are then sprung open, the section is inserted between the tourmalines, and the arms of the tongs are allowed to close. The instrument should be held close to the eye.

A modification of Norremberg's polariscope is, however, much better suited for this kind of work; and an efficient and cheap form of it, which the writer has recently planned for class-demonstration, and for the use of students, is now manufactured by Messrs. Watson, Bros., of Pall Mall. The general construction of the instrument is shown in Fig. 27,

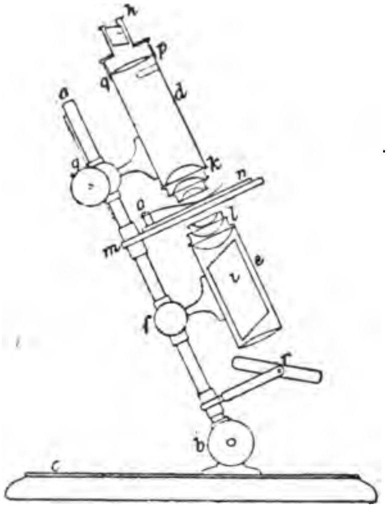

FIG. 27.

where *a* represents a square brass rod, attached by a joint, *b*, to a broad wooden foot, *c*. Upon this rod slide the mirror *r*, the arm of the tube *e*, the stage *m*, and the arm of the tube *d*. The latter is adjusted by a rack and pinion, *g*; but the tube *e* merely slides by moving the fitting at *f*.

At the lower end of tube *d* is a system of plano-convex lenses, with their plane surfaces directed downwards towards the stage while at the upper end of the tube *e* is a similar set of lenses, with their plane surfaces directed upwards towards the stage. The latter is simply a metal plate, with a circular aperture as large as the fitting of the upper lens of the lower system. A circular brass-plate, *n*, similarly perforated, rests on the stage, and rotates about a collar which works in the lower plate. The upper plate, or carrier, is provided with a pair of spring clips, *o*, which serve to hold the preparation.

Within the tube *e* is a Nicol's prism, *i*, the polarizer; while in a cap, *h*, which slides over the upper end of the tube *d*, is the analyser. The cap of the analyser turns on the end of the tube *d*. In the latter, and a little below the analyser, is a lens of low curvature, and just below this, at *q*, the tube is slotted, to permit the insertion of a quarter-undulation plate or a quartz-wedge.

More elaborate instruments, suitable for all the requirements of the crystallographer, are made by Fuess, Chevalier, Laurent, and other Continental makers; but their cost places them out of the reach of the majority of students. In lieu of such instruments, the microscope may be made to serve the same purpose by means of the arrangement described on p. 19.

Interference-figures (*Uniaxial*).—If, when the polariscope is arranged for convergent light, we insert a moderately thick plate of calcite, cut at right angles to the optic axis, we shall see, when the Nicols are crossed and ordinary white light is employed, a series of concentric, circular, iris-coloured rings * traversed by a dark cross, the arms of the latter lying in the directions N N, N′N′ of the principal sections of the Nicols.

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* The colours in each ring have a regular succession, as in Newton's rings; consequently each ring is a succession of concentric coloured rings, which merge one into the other, the same colour extending completely round the ring in any given zone. Hence these rings are termed isochromatic (like-coloured) curves. These, in the interference-figures of uniaxial crystals, are circles if the sections be cut perfectly at right angles to the optic axis.

This is an *interference-figure*, or an *axial figure*. The arms of the cross intersect at right angles in the centre of the figure, and the rings become narrower, and occur closer together the further they lie from the centre. Each ring shows the colours of the solar spectrum. On rotating the preparation, no change is visible in the figure; but, when we place the Nicols with their principal sections parallel, the dark cross gives place to a bright white one, and colours, complementary to those previously observed, now appear in the rings. Fig. 28 is a somewhat diagrammatic representation of a uniaxial interference-figure as seen in monochromatic light. Under such conditions, the field appears of the colour of the light employed, while the figure consists of rings of that colour alternating with dark rings, traversed by a dark cross, as indicated in Fig. 28, except that the cross, instead of being crude and sharply-defined, as in the figure, is shaded gradually away on the sides of the arms. This may be taken as a general type of uniaxial interference-figures. There are, however, exceptions, as seen in crystals in which an abnormal condition of tension exists, and in those which exhibit circular polarization. Of the latter, only two minerals can be cited as examples, namely, quartz and cinnabar (both crystallizing in the hexagonal system: rhombohedral). Crystals of arti-

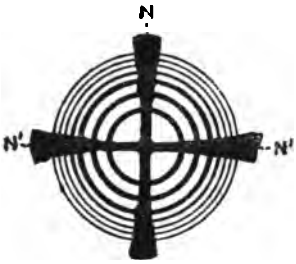

FIG. 28.

ficially-formed substances, however, not unfrequently possess this property.

Circular Polarization is evinced in certain crystals by their power of turning the plane of polarization in such a manner that it passes through the crystal, in the direction of the optic axis, in a screw-like manner. The amount of rotation of the plane of polarization being proportional to the thickness of the plate, but varying for light of different colours. The result of this is, that in sections cut at right angles to the optic axis, no extinction of light occurs during a complete revolution of the section. In plane or parallel polarized white light, the crystal-plate remains brilliantly illuminated in all azimuths, and the field exhibits a uniform colour or tint in any given position of the section between the stationary Nicols—assuming, of course, that the crystal-plate is not twinned, that it is homogeneous, and that it is of uniform thickness.

FIG. 29.

In convergent polarized light, such a section shows a series of iris-coloured concentric rings, traversed by a dark cross, which, however, does not extend inwards beyond the innermost ring. The area within this ring exhibits a uniform spread of colour *c*, Fig. 29, which varies, however, according to the thickness of the plate.

Crystals which possess the property of circular polarization, sometimes turn the plane of polarization to the right hand (dextro-gyrate), at others to the left (levi-gyrate). The dextro- or levi- gyrate properties of the crystal are also connected with its external form, as well as its molecular structure, the former being merely the expression of the latter. The external peculiarity in these crystals consists in the development of certain plagihedral, or tetartohedral, faces, a description of which will be found in any good mineralogical text-book. In sections viewed in convergent light (*e.g.*, quartz), the central area of the right-handed crystals presents a succession of different colours when the analyser is turned in the same direction as that in which the hands of a watch move; the succession being in this case from yellow through blue and violet to red. The rings also appear to dilate. In the case of a left-handed crystal, the succession is from yellow through red and violet to blue, and the rings appear to contract. In extremely thin axial sections of quartz, the rings are so widely separated that they do not appear in the field; and instead of the brilliantly-coloured central area, an almost colourless one is seen, traversed by the intersecting arms of a dusky cross.

FIG. 30.

When a right-handed plate of quartz is placed over a left-handed one, or *vice versâ*, a peculiar interference-figure, known as "Airy's spirals," is produced. These spirals may sometimes be met with in quartz-crystals, in which there is an intergrowth of right- and left- handed quartz and especially in amethyst. This appearance, as seen in monochromatic light is indicated in Fig. 30.

It should be noted, that in all axial sections, whether of uniaxial or of biaxial crystals, the rings of the interference-figures become more widely separated in thin than in thick sections. In the latter, the rings appear closely crowded together. The distance between the rings depends, however, not merely upon the thickness of the plate, but also upon the difference in the indices of refraction of the ordinary and extraordinary rays, and on the colour of the light employed. The greater the strength of the double refraction, the greater will be the difference in the respective velocities of the two rays and the more closely will the rings lie. In calcite, for instance, in which the double refraction is very strong, a moderately thin plate will show a very closely-packed system of rings.

Interference-figures (Biaxial). The interference-figures of some biaxial crystals approximate very closely in appearance to those of uniaxial crystals. This, however, is only seen when the angle formed by the intersection of the two optic axes is small.

Fig. 31.

The sections of biaxial crystals, prepared for examination in convergent light, should be cut, or, where practicable, cleaved, at right angles to the acute bisectrix.

If the section be taken *at right angles to one of the optic* *axes*, only a single system of concentric circular rings will be visible; and these will be traversed by a single straight dark bar, which rotates, and, in certain positions, becomes curved, when the section is turned (Fig. 31). Such a system of rings may be well seen in crystals of cane sugar (monoclinic), as one of the optic axes lies nearly normal to the broadest faces (orthopinacoids) of the crystal, or in cleavage-plates of bichromate of potash.

In sections of biaxial crystals, taken at right angles to the acute bisectrix, the interference-figure, seen between crossed Nicols in convergent polarized light, consists of a double series of oval rings, or lemniscata, of which the outermost coalesce. In white light these rings show a succession of colours, while in monochromatic light, the figure is represented by similarly-disposed dark rings. In either case, when the optic-axial plane is parallel to the principal section of one of the Nicols, the two systems of rings are symmetrically traversed by a narrow dark bar, which lies in the direction of the optic axial plane, while at right angles to this the two systems of rings are divided by a broad dark bar (Fig. 32). When the section is in the position which gives the interference-figure shown in Fig. 32, where N N, N′ N′, indicate the directions of the principal sections of the Nicols, it is said to be in the *normal position.*

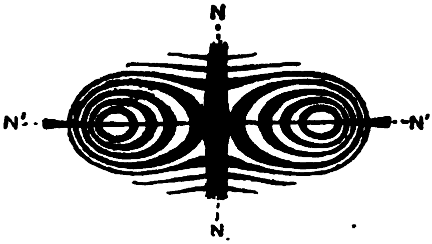

Fig. 32.

If now, the Nicols still remaining crossed, we turn the section so that the opic-axial plane *a p* stands at 45° to the principal sections N N, N′ N′ of the Nicols (Fig. 33), the figure will be seen to have undergone a marked change; the two rectangularly-crossed bars have disappeared, breaking up into two dark curved brushes (hyperbolæ), each of which crosses the innermost ring of each system of oval rings. The portion of the hyperbola where it crosses one of these first rings, is fringed with colour, the colour on one side of the bar differing from that on the other. There is also a definite distribution of the colours fringing the rings, of which special note will subsequently have to be taken.

When the section is in the position which gives the interference figure shown in Fig. 33, it is said to be in the *diagonal position.*

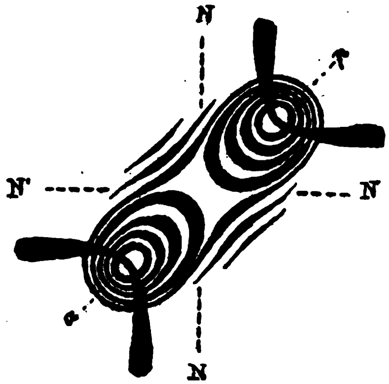

FIG. 33.

These interference-figures result from the polarized light, which passes through the lower system of plano-convex lenses of the polariscope, forming a double cone of polarized light within the doubly-refracting crystal plate. In the direction of the optic axis there is no double refraction, nor is there any in the two directions corresponding with the principal sections of the crossed Nicols, the ray in one of these directions passing through as an ordinary, in the other direction as an extraordinary ray; but, in other azimuths, the different rays,—which form a succession of cones lying one within the other and varying, for each cone, in their inclination to the optic axis,—undergo double refraction, so that each cone, in the case of a negative uniaxial crystal, will consist of an inner series of extraordinary rays vibrating in planes radial to the optic axis, and an outer series of the more refracted ordinary rays vibrating tangentially, and at right angles to the extraordinary rays. In positive uniaxial crystals, the ordinary rays of each cone will vibrate radially, and the extraordinary tangentially.

In either case, the vibrations of the more or less retarded rays, on entering the analyser, become reduced to the same plane, and interference ensues—the result, if white light be used, being circular coloured rings, the colours corresponding with the different refrangibilities of the different rays. Each ring will, therefore, consist of a series of concentric isochromatic zones.

With the increased obliquity of the rays in the cones, as they succeed one another from the centre towards the margin, so an increased difference of phase occurs.

In the analyser each of these rays again becomes split into two, the ordinary ray being in each case abolished by total reflection from the film of balsam which cements the halves of the analyser, while the extraordinary rays, which differ by uneven numbers of half-wave lengths, become reduced to the same plane of vibration (*i.e.*, they have to vibrate parallel to the principal section of the analyser), and they consequently interfere and produce coloured rings. These occupy the positions which, in monochromatic light, would give dark rings, since the differences in phase would here amount to uneven numbers of half-wave lengths, while the interspaces between the rings result from rays which differ in phase by even numbers of half-wave lengths.

In Fig. 34, an endeavour is made to show the relation of the rings under the respective conditions of monochromatic and of ordinary white light. Only half of the interference-figure is represented.

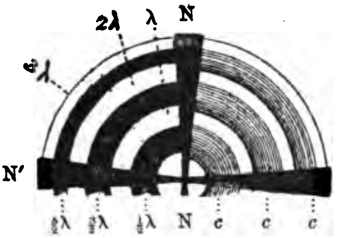

FIG. 34.

The lines N N, N′N′ denote the principal sections of the crossed Nicols.

The left quadrant indicates the appearance in monochromatic, and the right quadrant that in white light.

In the left quadrant the first dark ring from the centre results from interference due to a difference of phase of $\frac{1}{2}\lambda$, the second dark ring to a difference of $\frac{3}{2}\lambda$, and the third dark ring to $\frac{5}{2}\lambda$. The differences of phase in the alternate clear rings are $\lambda = \frac{1}{2}\lambda \times 2$, $2\lambda = \frac{1}{2}\lambda \times 4$, and $3\lambda = \frac{1}{2}\lambda \times 6$, or even numbers of half-wave lengths, so that in these intermediate rings no interference takes place.

In the right quadrant, *c*, *c*, *c*, represent iris-coloured rings, corresponding in position to the dark rings seen in monochromatic light. Here, again, the differences in phase are $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}\lambda$, or uneven numbers of half-wave lengths, so that, when the vibrations are reduced to the same plane by the analyser, interference, accompanied by colour, results. It should, however, be remembered, that this diagram expresses only a partial truth, since, if the dark rings be represented as seen when red light is employed, those seen when monochromatic light of other colours is used will be found to occupy somewhat different positions; for this reason the coloured bands *c, c, c,* have been represented as rather broader than the dark bands.

In the case of biaxial crystals it has already been stated that when a section is taken normal to one of the optic axes, the interference-figure consists of circular, or approximately circular, rings traversed by a dark brush; but that when the section is made at right angles to one of the bisectrices, two systems of rings are developed, and these rings are not circular. On referring again to Fig. 26, it will be remembered that rays emergent at right angles to the plane *t t* constitute a cylinder. It is manifest, then, that in a direction normal to the axis of such a cylinder we should have a circular section, while in a direction oblique to its axis the cylinder would give an elliptical section.

We may, in fact, realize to some extent the nature of this difference by cutting through an ordinary drawing pencil obliquely, and comparing this cut surface with the circular end of the pencil.

In the interference-figures seen in sections taken at right angles to the acute bisectrix of a biaxial crystal, certain rays are transmitted which are parallel to each of the optic axes. In the concentric cones of polarized light which enter the section there are, however, a vast number which follow directions equally inclined with regard to one or other of the optic axes, and it is these rays which by their interference give rise to the oval rings. As in the case of the uniaxial interference-figures, each polarized ray which enters the section of the crystal is doubly refracted; and one of these rays is then constrained to vibrate in a plane at right angles to the other. We have, therefore, again, luminous vibrations occurring at right angles to one another about each of the optic axes; but the explanation of the way in which the biaxial interference-figure is produced differs from that applicable to uniaxial crystals.

If to any number of points in the circles represented in Fig. 35, we draw radii from the centres, *p p′*, and by straight lines, as *p′ a*, *p′ b*, *p′ c*, etc., join those points with the centre of the opposite circle, and bisect the angles *p b p′*, *p c p′*, etc., the lines bisecting these angles will give the directions in which one set of the doubly-refracted rays will vibrate, while the other set will vibrate in planes at right angles to these directions, as at *e*, *f*, *g*, etc. On entering the analyser, one of these sets of vibrations will be abolished by total reflection, while the other set, when reduced to the plane of the principal section of the analyser, will be transmitted; but since they possess differences of phase they will interfere, and give coloured oval rings when white light is used, or, in monochromatic light, dark oval rings. In the normal position of the plate a narrow, dark bar will be seen in the direction N′N′, and a broad one in the direction N N. On turning the crystal plate, the cross formed by these dark bars separates into two dark brushes, as already explained on page 67.

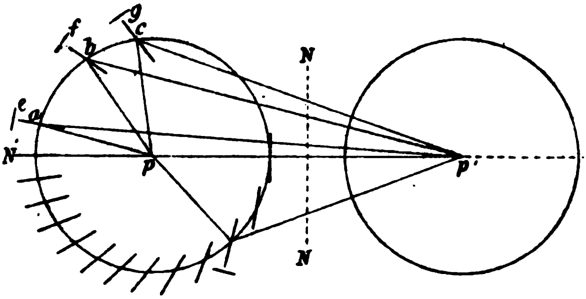

Fig. 35.

For further explanation of these phenomena, the student should consult larger works on this subject.

Dispersion.—It has already been mentioned, that in the interference-figures of biaxial crystals the distribution of the colours is different in different minerals.

If, as an example, we take a section, made at right angles to the acute bisectrix, of a mineral crystallizing in the rhombic system, such as barytes, we shall find that the insides of the first, or polar rings, are fringed with red, while the outer sides will be fringed with blue. The letters ρ and v are usually employed to denote the extreme colours of the spectrum, red and violet.

In Fig. 36, such an axial figure is shown in the normal position. The coloured fringes of the innermost rings are represented by the letters ρ = red, v = blue; while, to render this and the succeeding diagrams more clear, light shading is also used to denote red, darker shading representing blue. Fig. 37 shows the change brought about by turning the section into the diagonal position, so that the optic axial plane stands at 45° to the principal sections of the Nicols. Here we note that blue fringes the convex sides of both hyperbolæ, while their concave sides are fringed with red. The inner sides of both rings are also fringed with red, and their outer sides with blue.

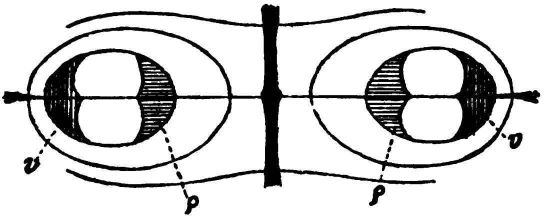

FIG. 36.

This is an example of what is known as *rhombic dispersion.*

All crystals of the rhombic system do not, however, show the same colours in the same situations, although the relative distribution of the colours, both in the normal and diagonal positions, is always similar. For instance, in this particular case the dispersion for red is said to be less than that for blue

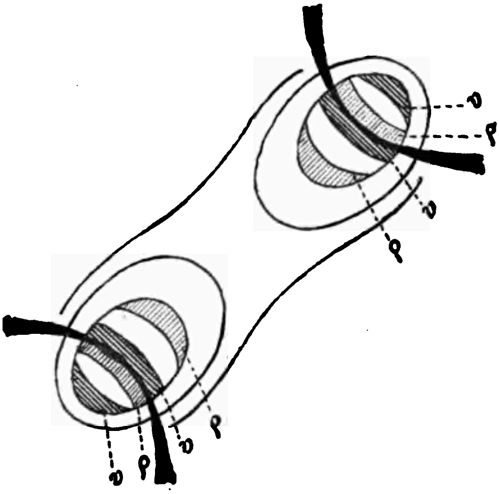

Fig. 37.

light, a condition expressed by $\rho < v$, but in other instances we meet with a greater dispersion for the red than for the blue rays, which is expressed by $\rho > v$.

In the latter instance the innermost rings will, in the normal position, be fringed with blue inside and red outside, while in the diagonal position the hyperbolæ are fringed with red on their convex, and blue on their concave sides, and the rings are blue on their inner, and red on their outer, sides.

A model to illustrate rhombic dispersion may easily be made by taking an ordinary visiting card on which lines are drawn, as indicated in Fig. 38. A needle can then be stuck at right angles through the card in the point in which the lines intersect, to represent the optic normal, and the model is complete.

Let us now consider what the lines upon the card mean. The line 𝔠 is the axis of least optical elasticity, and the line 𝔞 that of the greatest. The former is also the acute bisectrix, and it coincides with, or is parallel to, one of the crystallographic axes, while the latter is the obtuse bisectrix, and also coincides with, or is parallel to, a crystallographic axis. The dotted lines $\rho\ \rho$, $\rho\ \rho$, are the optic axes for red, while those marked $v\ v$, $v\ v$, are the optic axes for blue light. The card itself upon which the lines are drawn, represents the optic-axial plane, and the needle 𝔟 the axis of mean elasticity, which is also the optic normal, and is likewise coincident with or parallel to another of the crystallographic axes. According to Schrauf, this and other rhombic crystals should be so placed that the acute bisectrix should always be the vertical axis, and in this case the axis of least elasticity would be taken as the vertical axis; but it is also usual for a crystal of barytes, for example, to be read in such a manner that the axis of mean elasticity 𝔟 is taken as the vertical axis ($c = \mathfrak{b}$), in which case the optic-axial plane will be parallel to the basal planes of the crystal. If we examine a section in which we have $\rho < v$ first in red, and then in blue light, we shall find that in the former case the two systems of rings appear much closer together than they do in blue light. In Fig. 39, the two innermost rings and their hyperbolæ are represented in the positions which they would relatively occupy in red and blue light.

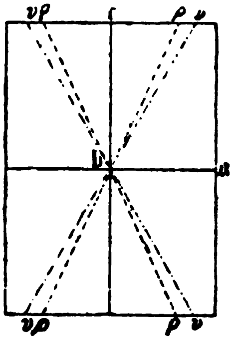

FIG. 38.

The thick circles and curves denote the rings and hyperbolæ in red, while the thin lines and curves indicate the rings and hyperbolæ in blue light.

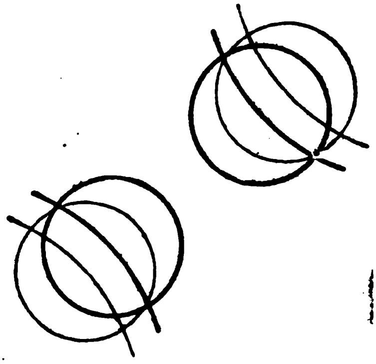

FIG. 39.

What we see through the polariscope is, however, quite different; for where we see the rings in red light there, in white light we meet with a complementary blue, the red being abolished, and only the residual colours of the spectrum being visible. We also find that where the rings occurred in blue light, no blue appears, but only the residual rays for the red portion of the spectrum.

The chromatic fringes of the hyperbolæ, which we see in the interference-figure, represent, therefore, an apparent reversal of the true dispersion, for in the case $\rho < v$, the angle formed by the intersection of the optic axes for red is less than that of the optic axes for blue light; yet in the interference-figure the hyperbolæ are fringed with blue towards the inside, and with red towards the outside of the figure, as indicated in Fig. 37.

In determining the dispersion of a crystal, it is therefore important always to bear in mind this apparent reversal of the colours which border the hyperbolæ.

In the rhombic system the dispersion is always symmetrical in relation to the bisectrix; and the bisectrix is common for light of all colours.

There are a few crystals occurring in the rhombic system in which the dispersion for different colours takes place in different planes. The mineral which shows this peculiarity in the most marked manner is Brookite, the rhombic form of titanic acid. Here the dispersion of the optic axes for red occurs in a plane at right angles to that in which the optic axes for green light are situated; but the dispersion both for red and for green is still perfectly symmetrical with reference to the common bisectrix.

Nitre affords a good example of rhombic dispersion, in which we have $\rho < v$, as in barytes.

Examples of $\rho > v$ may be well seen in sections of cerussite and aragonite.

In the monoclinic system various kinds of dispersion are met with, namely, *inclined*, *horizontal*, and *crossed*.

Inclined Dispersion.—The interference-figure in this case is indicated in Figs. 40 and 41. In the former the distribution of colours in the first or innermost rings is denoted by shading, as in the preceding figures. It will usually be seen that the rings are not always of the same size and shape, also that the broader bar of the dark cross is nearer to the larger ring; although, in Fig. 40, the rings are represented of about the same size. A one-sided distribution of the colours is also to

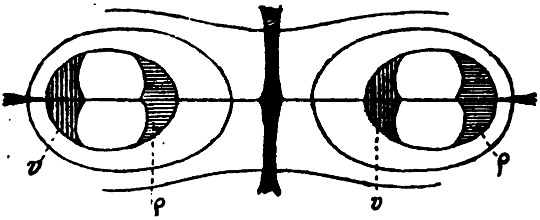

FIG. 40.

be noted, the red, in the case here figured, fringing the right sides of both rings, while their left sides are fringed with blue. On turning the plate so that the optic-axial plane lies at 45° to the principal sections of the Nicols, the distribution of colours indicated in Fig. 41 is seen. The convex side of one hyperbola, and the concave side of the other being fringed with the same colour. Selenite and diopside afford good examples of inclined dispersion. In some crystals of adularia (a variety of orthoclase) inclined dispersion may also be observed; but the phenomenon is not so strongly marked as in the examples just mentioned.

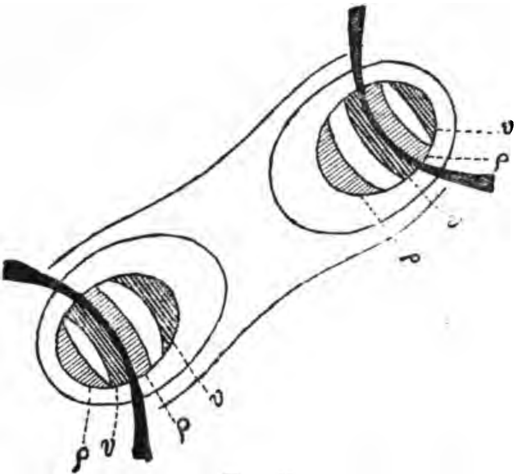

FIG. 41.

In cases of inclined dispersion, the optic axes always lie in the plane of symmetry, *i.e.*, in a plane parallel to the clinopinacoids.

Horizontal Dispersion.—In this case the optic axes lie in a plane at right angles to the plane of symmetry and parallel to the orthodiagonal; and the acute bisectrix is situated at right angles to the orthodiagonal, so that the obtuse bisectrix coincides with, or is parallel to, the latter.

The appearances presented by the interference-figures under these conditions are indicated in Fig. 42 (normal position), and Fig. 43 (diagonal position). In the normal position we note that the narrower dark bar, lying in the plane of the optic axes, is fringed, where it crosses the innermost rings, with blue on the one side of the bar, and with red on the other, the maximum of red or of blue in each ring occurring on opposite sides of that ring, while the upper inside edges of both rings

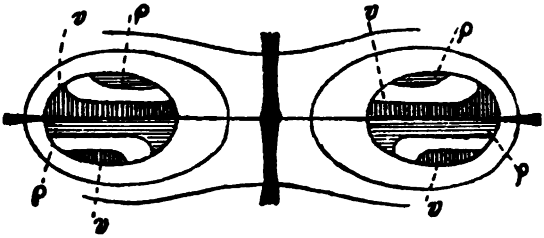

FIG. 42.

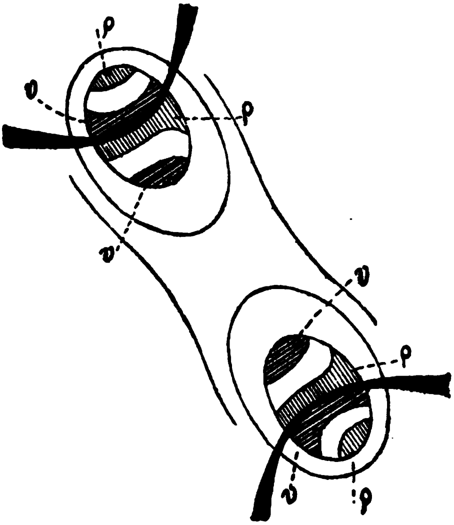

FIG. 43.

are fringed with the same colour, *e.g.*, red, as in Fig. 42, their lower inside edges being also fringed alike, but with a different colour, *e.g.*, blue, as in Fig. 42.

In the diagonal position, Fig. 43, the colours are disposed in a somewhat similar manner; but we here note that the convex sides of the hyperbolæ are fringed with the same colour, red, while blue fringes their concave sides.

Sections of adularia, taken at right angles to the acute bisectrix, afford good examples of horizontal dispersion.

Crossed Dispersion.—If from a crystal of borax a plate be cut in a direction at right angles to the acute bisectrix, and examined in convergent polarized light, the colours of the interference-figure will be seen, when the plate is in the normal position, to be distributed in the manner indicated in Fig. 44.

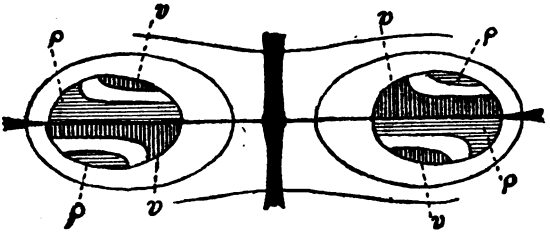

FIG. 44.

Within one of the rings the colours are arranged just as in horizontal dispersion, but in the other ring this is not the case; and on comparing the colours in the two rings we shall find that they are arranged chequerwise, the horizontal bar being fringed with blue above in the right ring, and blue below in the left, the maximum of blue lying towards the inside of each ring. In the diagonal position, the colours are distributed much as in the diagonal position of the interference-figure of a crystal in which horizontal dispersion occurs, *i.e.*, as in Fig. 43, except that in the colours fringing the hyperbolæ the greatest development for the same colour is on one side of one ring and on the opposite side of the other.

It remains to be explained how these different kinds of dispersion are brought about; and in studying the conditions which produce them, the student will derive benefit from constructing cardboard or, still better, wire models, to show the relative positions of the crystallographic axes, the axes of elasticity, and the optic axes for light of different colours. For the latter, the axes for red and violet will suffice, as they represent the extremes of the spectrum.

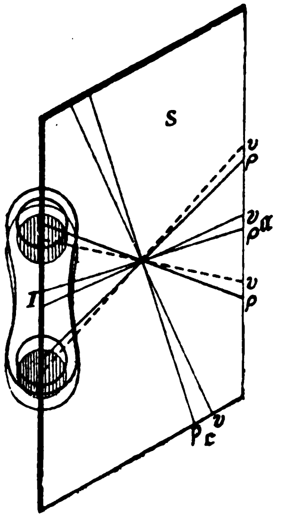

FIG. 45.

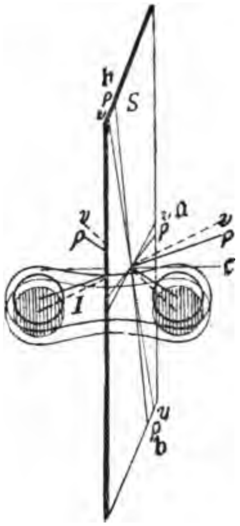

FIG. 46.

In Figs. 45, 46, and 47, S represents the plane of symmetry in a monoclinic crystal. Upon this plane, in each case, lines are drawn which represent, in the first instance, optic axes and axes of elasticity, in the second and third cases, axes of elasticity only. The plane of symmetry is represented in a somewhat different position in each drawing, but in every instance the thick vertical line is assumed to be parallel to the vertical crystallographic axis, and the thick oblique line to the clinodiagonal.

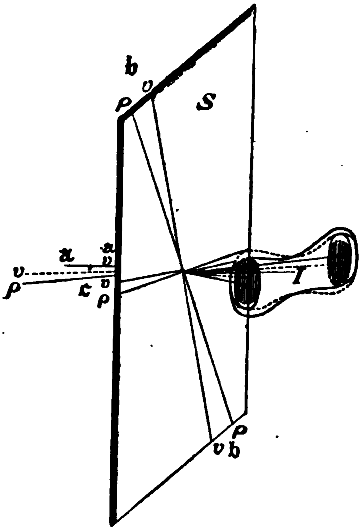

FIG. 47.

In Fig. 45 the diagram represents a case of inclined dispersion; and the interference-figure I is drawn as if it were a tangible object cut out of a transparent substance, such as a plate of mica, and fixed at right angles to a rhomboidal board S, which is supposed to be the plane of symmetry of a monoclinic crystal. On the right hand, or further edge of the plane S, two continuous lines, marked *ρ ρ*, are shown. These are the optic axes for red light. They intersect and pass through the centres of the first rings for red light in the interference-figure I. Again, on the remote edge of the plane S, two finely-dotted lines are shown. These are marked *v v*. They are the optic axes for blue light. They intersect in the same point as the optic axes for red light, and pass through the centres of the first rings for blue light, the areas of which are denoted by vertical shading.

We have then at I two interference-figures partially superposed, the one being shown by continuous, and the other by dotted lines, the latter appearing to be shifted downwards in the direction of the optic-axial plane.

The lines $\mathfrak{a} \upsilon$ $\mathfrak{a} \rho$ are the acute bisectrices for blue and for red light respectively. They are also axes of greatest elasticity for those colours. The lines $\mathfrak{c} \upsilon$ $\mathfrak{c} \rho$ are also respectively the obtuse bisectrices for blue and for red light, and they are the axes of least elasticity for those colours. The optic normal, or axis of mean elasticity, passes through the point in which the optic axes and the bisectrices intersect, and lies at right angles to the plane S. To avoid confusion, it is, however, omitted in the drawing.

From this figure it will be seen that the bisectrices for red, blue, and indeed for all intermediate colours, lie in the plane of symmetry, but they make different angles with one another.

The common plane of the optic axes for red, blue, and all intermediate colours, is likewise the plane of symmetry; and it is also in this plane that the interference-figures are displaced.

Fig. 46 represents a case of horizontal dispersion. Here, again, S is the plane of symmetry; and it will be seen that the optic axes, for red, ρ, and for blue, υ, lie in planes which are situated at right angles to the plane of symmetry; but the planes, in which the optic axes for red and blue respectively lie, intersect, so that the interference-figure for blue is shifted in the direction of the symmetral plane somewhat below that for red. The optic-axial planes in both cases are parallel to one another, and lie at right angles to the plane of symmetry. The acute bisectrix for red, $\mathfrak{a} \rho$, and that for blue, $\mathfrak{a} \upsilon$, lie in the plane of symmetry, and, of course, intersect at the same angle as the corresponding optic-axial planes. The obtuse bisectrix $\mathfrak{c}$ (also the axis of least elasticity, also the orthodiagonal), is common for light of all colours, and is situated at right angles to the plane of symmetry. The lines $\mathfrak{b}\,\rho$, $\mathfrak{b}\,v$ are the optic normals for red and blue respectively.

Fig. 47 shows a case of crossed dispersion. Again, S is the symmetral plane; $\mathfrak{a}$ is the axis of greatest elasticity, also the orthodiagonal, also the acute bisectrix. In this case the acute bisectrix is common for all colours. The obtuse bisectrix, for red, $\mathfrak{c}\,\rho$, and that for blue, $\mathfrak{c}\,v$, lie in the plane of symmetry; but they make slight angles with one another, and consequently the optic axes,—for red, ρ, and for blue, v,—which lie in planes at right angles to the symmetral plane, also intersect; the plane of the optic axes for red making a correspondingly small angle with the plane of the optic axes for blue light. We may therefore liken the acute bisectrix $\mathfrak{a}$ to a pivot, upon which the planes of the optic axes for different colours undergo a slight rotatory displacement, in consequence of which the interference figures for the different colours become more or less turned about the orthodiagonal $\mathfrak{a}$. This shifting of the interference-figures for different colours is represented in the diagram at I. (fig. 47), where that for red, shown by continuous lines, is slightly crossed by the interference-figure for blue, indicated by dotted lines; the areas of the inner rings for blue being denoted by vertical shading. The optic normals for red, $\mathfrak{b}\,\rho$, and blue, $\mathfrak{b}\,v$, lie in the symmetral plane. Inclined, horizontal, and crossed dispersion also occur in crystals belonging to the triclinic system, a single crystal sometimes showing more than one kind of dispersion. In axinite, for instance, we meet with both inclined and horizontal dispersion.

Interpretation of partially visible Interference-figures.—In sections of crystals which are not taken normal to a bisectrix, a condition which usually occurs in microscopic preparations of rocks, and in cleavage-plates of minerals in which the cleavage planes make an angle with one or other of the bisectrices, it is common to see, in convergent polarized light, only an imperfect interference-figure. In very thin sections, indeed, it is often difficult for the beginner to realize that he is looking at an interference-figure at all, the impression of a dusky smudge being, probably, all that is conveyed to his untutored retina. The following examples may serve to indicate that these obscure markings have their meaning :*—

Partial Interference-figures of Uniaxial Crystals.—In the case of uniaxial crystals, when the optic axis lies within the field of the polariscope, it is easy enough to recognise what portion of the interference-figure is before us. In Fig. 48, however, the optic axis lies just outside the boundary of the field, and the interference-figure is so situated that a line drawn through the optic axis and the centre of the field would lie at 45° to the principal sections of the crossed Nicols. In this instance two of the arms *a a′* of the dark cross are visible, and part of a coloured ring, *r*. In reality, however, the arms of the cross are never sharply defined at their edges, and in very thin sections they appear merely as blurred, shadowy bars; while in such cases the rings are usually so wide that they do not come into the field.

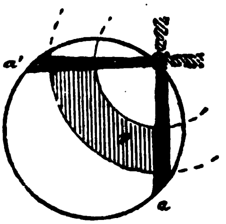

FIG. 48.

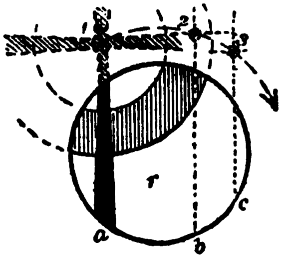

FIG. 49.

In Fig. 49, the interference-figure is so situated that the

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* For a more complete series of figures, the student should consult the plates in Fouqué and Lévy's "Minéralogie micrographique," or that in Hussak's "Anleitung zum Bestimmen der Gesteinbildenden Mineralien."

optic axis lies further out of the field than in the preceding example, the arms of the dark cross intersecting in the point marked 1. A single dark bar now traverses the left-hand side of the field in a vertical direction. On turning the stage so that the axis, lying outside the field, travels round in the direction of the curved arrow, the dark bar will be seen to march slowly across the field from left to right, still retaining its vertical direction, and consecutively occupying the positions shown by the dotted lines *2b*, *3c*, until it leaves the field. If the rotation be continued in the same direction, the point in which the arms of the cross intersect will gradually reach the

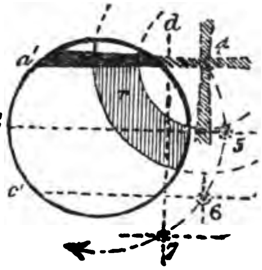

FIG. 50.

position 4, Fig. 50. By this time another arm of the cross has appeared in the field, but this lies in a horizontal position, *4a'*; and as the rotation of the stage is continued, the horizontal bar will march down the field, occupying successively the positions *5b'*, *6c'*, etc., until it passes the lower edge of the field, and is lost to view. We see, then, that in sections of uniaxial crystals, when the optic axis lies outside the field of the polariscope, a straight, dark bar traverses the field in a direction parallel to the principal section of one of the Nicols, and, during rotation of the stage, marches straight across the field until it disappears, when another bar enters in a direction parallel to the principal section of the other Nicol, and moves with like regularity, in a direction at right angles to that pursued by the former bar, until it too disappears from view.

This phenomenon often helps to decide whether a partial interference-figure should be referred to a uniaxial crystal or not.

Partial Interference-figures of Biaxial Crystals.—In those cases in which one of the optic axes lies within the field of the microscope, the dark bar which is then visible is easily distinguished from one of the arms of the cross in a uniaxial crystal, since, on rotation, it passes from a straight into a curved bar, which sweeps diagonally across the field, and never travels straight across in one direction, as do the arms of the cross in uniaxial crystals. The same oblique sweep of the brush may also be seen when the stage is rotated, in those cases in which the centre of the field lies between one of the optic axes and the thick, dark bar of the cross seen in the normal position of the section. This condition is shown in Figs. 51, 52, and 53. In all of these figures both of the optic axes lie outside the field, as well as the bisectrix, represented by the thick, dark bar, which would cross the vertical dark bar in Fig. 51 at right angles, at a point far up the page.

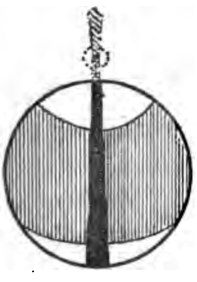

FIG. 51.

FIG. 52.

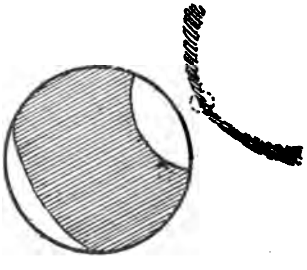

FIG. 53.

Fig. 51 shows part of the narrower bar of the cross seen in the normal position of the section. In Fig. 52 a slight rotation of the stage has broken the cross up into hyperbolæ, one of which sweeps obliquely as a dark brush across the right of the field. In Fig. 53, a further rotation has thrown the hyperbola completely out of the field, and, even in moderately thick sections, segments of the inner rings would alone be visible. In Figs. 54, 55, and 56, we have corresponding positions of the crystal plate with reference to the principal sections of the crossed Nicols; but in all of these examples the bisectrix, represented by the broad dark bar, shown in Fig. 54, lies within the field of the polariscope or microscope. In Fig. 54, the section lies in the normal position, *i.e.*, with the broader bar of the cross vertical or, as in the figure, horizontal. In Fig. 55, a rotation of 25° to 30° has caused such a change, that only portions of the hyperbolic brushes are visible on the right and left margins of the field, together with portions of the two systems of coloured rings or lemniscata. In Fig. 56, the hyperbolæ lie outside the field, owing to the section having undergone further rotation, until the optic-axial plane stands at 45° to the principal sections of the Nicols. Portions of the lemniscata are alone visible in this instance. The examples here given suffice to show the general nature of the changes which may be observed in different positions when

FIG. 54.

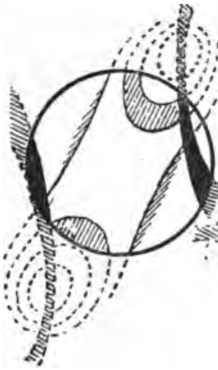

FIG. 55.

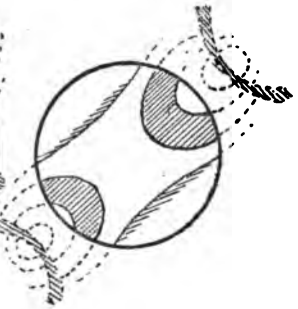

FIG. 56.

sections or cleavage plates, lying askew to a bisectrix, are examined in convergent polarized light.

Measurement of the Optic-Axial Angles.—For this purpose plates cut at right angles to the acute bisectrix should be used.

Each of the optic axes makes an angle, V, with the acute bisectrix; and the two axes consequently enclose an angle, which is denoted by 2V. This is termed the *real angle* of the optic axes. Each ray, however, which travels along an optic axis, again undergoes refraction when it emerges from the crystal plate into the air, and forms an angle, E, Fig. 57,

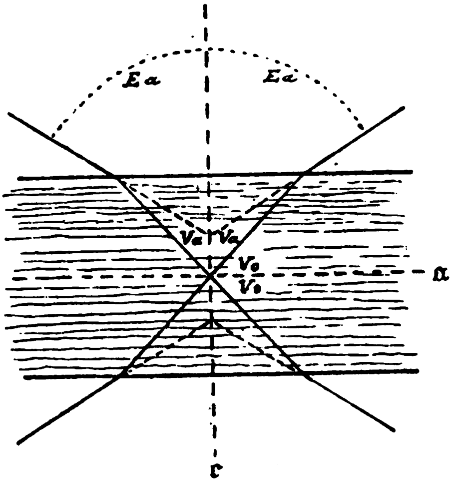

Fig 57.

with the acute bisectrix (in the case of a positive crystal, the acute bisectrix would be the axis of least elasticity, 𝔠, as shown in the figure). A similar angle, E, is also formed on the other side of the bisectrix by the other optic axis, and these two angles constitute the angle 2E, which is termed the *apparent angle*. This is always greater than the angle 2V.

The half of the acute real angle is distinguished from that of the obtuse by the symbol V*a*, the half of the obtuse real angle being represented by the symbol V*o*, Fig. 57. In the same way the half of the acute apparent angle in air is denoted by E*a*, and that of the obtuse by E*o*.

The real angle of the optic axes may be directly measured by employing a cylinder, so cut from the crystal that its axis is parallel to the optic normal, or axis of mean elasticity, 𝔟; or a sphere cut from the crystal may be also used, since in either case the rays emerge at right angles to the limiting surface, and consequently undergo no refraction on emergence. The ordinary method, however, is to employ a plate cut at right angles to the acute bisectrix. The instrument used consists of a goniometer, combined with a polariscope arranged for convergent light, the whole being so contrived that the crystal plate is held in a pair of forceps attached to the goniometer. The forceps can be raised, lowered, traversed, or turned, for the purpose of adjusting and centring the plate. The polariscope is provided with crossed spider-lines; and the crystal plate is brought into position by turning the forceps until the convex side (vertex) of one of the hyperbolæ, where it crosses a first ring, is apparently in contact with the vertical spider line. A reading of the goniometer is then taken, and it is afterwards turned until the vertex of the other hyperbola is brought into a precisely similar position. The angle through which the goniometer has been turned is the apparent angle in air. The instrument is also so arranged that the optic-axial angle can be measured when the crystal plate is immersed in a little parallel-faced glass reservoir containing almond oil, which has a refractive index much nearer to that of the crystal than air. By this means the refraction of the emergent rays is reduced, so that the optic-axial angle can be measured in crystals which, from their wide angle and high refraction, would have the rays following the optic axes totally reflected in air.

If E = the apparent semi-axial angle in air,
$\begin{cases} Ha = \text{the apparent semi-acute angle in oil,} \\ Ho = \text{the apparent semi-obtuse angle in oil,} \end{cases}$
Va = the real semi-acute angle,
Vo = the real semi-obtuse angle,
n = the refractive index of the oil,
β = the mean refractive index of the crystal,

Then—

$$\sin E = n \sin Ha\,;\ \sin Va = \frac{n}{\beta} \sin Ha\,;\ \sin Vo = \frac{n}{\beta} \sin Ho.$$

By these formulæ the true interior angle of the optic axes may be calculated from the apparent angle which has been measured, the mean refractive index β of the crystal having been previously ascertained.

When it is possible to measure the obtuse as well as the acute apparent angle, the true angle of the optic axes and the mean refractive index of the crystal can be determined, since $\sin Vo = \cos Va$. Hence—

$$\tan Va = \frac{\sin Ha}{\sin Ho}\,;\ \beta = n\frac{\sin Ha}{\sin Va} = n\frac{\sin Ho}{\cos Va} = \frac{\sin E}{\sin Va}.$$

In measuring the angles of the optic axes, it is always desirable to use monochromatic light. Arrangements similar in principle to those already described, but on a smaller scale, are adapted for use upon the stage of the microscope. For further particulars upon this branch of investigation the student must consult the larger text-books.

Determination of the Different Axes of Elasticity, or Determination of the Optical Sign of a Crystal.—Mica is biaxial and negative, consequently the acute bisectrix is the axis of greatest elasticity and the obtuse bisectrix that of least. The planes of cleavage in the micas are almost precisely at right angles to the acute bisectrix; hence the obtuse bisectrix, or axis of least elasticity, and the optic normal, or axis of mean elasticity, lie in a plane parallel to the cleavage.

If upon such a mica-plate,—preferably one of wide optic-axial angle,—viewed in convergent polarized light, we place another of equal thickness, the obtuse bisectrix of the one being set parallel to that of the other, the rings of the interference-figure will appear to be narrower and less widely separated than they did in the single plate. If, now, a third plate of similar thickness be superposed, the rings will appear still narrower and more closely packed. By the superposition of additional plates, the narrowing of the rings and the diminution of the spaces between them becomes more and more marked; and with each addition to the pile the two systems of rings appear to draw more closely together. On removing one plate after another, we see the rings widen and the spaces between them increase.

The student should therefore bear in mind, that the effect of thinning a section is to make the rings of its interference-figure appear broader, larger, and more widely spaced, while the effect of thickening is to make the rings appear narrower, smaller, and more closely packed. It should also be noted that the phenomena indicative of thickening were produced when the mica plates were arranged with their axes of minimum elasticity parallel.

If we take a plate of barytes, cut at right angles to the acute bisectrix, and place it in convergent polarized light, we have another example of a biaxial interference-figure, but in this case the crystal is positive; *i.e.*, the acute bisectrix is the axis of least elasticity, $\mathfrak{c}$. If, now, we take a plate of quartz (which has positive double refraction) cut parallel to the optic axis or principal crystallographic axis, and insert the plate between the analyser and the plate of barytes, in such a manner that the optic-axial plane of the latter is parallel to the principal axis of the quartz plate, we shall see (the barytes being in the diagonal position) that the hyperbolæ of the interference-figure of the barytes are no longer black, but exhibit similar colours, according to the thickness of the quartz plate; and we shall also see that the rings appear somewhat larger. If, instead of the parallel-faced quartz-plate, we take a quartz wedge, so cut that the long sides of the wedge are parallel to the principal axis of the quartz, while the thin end is at right angles to the principal axis, and insert this wedge in the polariscope, so that the principal axis of the wedge passes in a direction *parallel to the optic-axial plane* of the barytes, we shall see, as we gradually insert the wedge, that the rings of the interference-figure of the barytes seem to expand and travel from the margin of the field towards one another, until, one pair after another, they unite and form lemniscata, which appear to travel outwards towards the margin of the field. In this case the entire interference-figure apparently contracts in the direction of the optic-axial plane, while in a direction at right angles to this, it seems to expand.

In our section of barytes the acute bisectrix is the axis of least elasticity. The axes of greatest and mean elasticity therefore lie in a plane parallel to the surfaces of the section, the former being parallel and the latter at right angles to the optic-axial plane. The effect produced by the insertion of the quartz wedge in the direction of the optic-axial plane was indicative of a thickening of the plate, because the axis of greater elasticity in the wedge was parallel to the axis of greatest elasticity in the barytes. Had the wedge been inserted in a direction at right angles to the optic-axial plane of the barytes, the effect would not have been one suggestive of thickening, because the axis of greater elasticity in the wedge would have been parallel to an axis of less elasticity, *i.e.*, the axis of mean elasticity in the barytes. Now we know that the axis of mean elasticity is never a bisectrix; therefore, as the bisectrix lying in the plane of the section was one of greater elasticity, it is evident that the other axis of elasticity represented the mean, while the bisectrix normal to the plane of section must consequently be the axis of least elasticity.

Again, if we take a section cut at right angles to the acute bisectrix of a negative biaxial crystal, such as aragonite, and place it in convergent polarized light, in the diagonal position, we shall notice that the effect of thickening is produced when the quartz-wedge is inserted with its principal axis in a direction *at right angles to the optic-axial plane.* Clearly, then, the elasticity in this direction is greater than that in the direction parallel to the optic-axial plane; but as it is normal to the optic-axial plane, it is therefore the optic normal, or axis of mean elasticity. Since, then, the elasticity of the mean axis is greater than that of the other axis lying in the plane of section, the latter must be the axis of least elasticity; and the remaining axis of elasticity, which lies at right angles to the planes of section, must be that of greatest elasticity. By means, therefore, of a plate, or wedge, having two of its sides parallel to a direction of known elasticity, we can determine the different directions of elasticity in a biaxial crystal, also its optical sign. For, if the appearance of thickening be produced when the principal axis of the quartz-wedge is inserted *along* the optic-axial plane of the interference-figure, the biaxial crystal has *positive* double refraction; but if the apparent thickening be produced when the wedge is inserted *across* the optic-axial plane, the double refraction of the crystal is then *negative.*

The different axes of elasticity in a crystal, also its optical sign, may likewise be recognised by focussing the crystal in the field of the microscope, between crossed Nicols, turning the stage so that a known crystallographic edge lies at 45° to the principal sections of the Nicols, and then inserting the quartz wedge below the analyser in the same direction, when the bars of colour which cross the wedge parallel to its thin edge will appear to be thrown either nearer to or further back from the thin edge of the wedge. In the former case, the rise in colour denotes that the crystal is positive; in the latter, the fall in colour shows that it is negative.

The expressions "rise" and "fall in colour" may be further explained by stating that the quartz-wedge exhibits in parallel polarized light a number of coloured bars, shading one into the other, and lying, as already mentioned, parallel to the thin edge of the wedge. These coloured bars constitute a progressive series of spectra, the colours following the order of Newton's scale. Thus, at the thin edge of the wedge we have the colours of the first or lowest order, and at thicker parts of the wedge recurring spectra, but of successively higher orders.

NEWTON'S COLOUR SCALE.

Order.	Number in Scale.	Retardation in Thousandths of a Millimetre.	Interference Colour between crossed Nicols.	
1st	1	0	Black	Between parallel Nicols the complementary-interference colours are seen.
	2	40	Iron-grey	
	3	97	Lavender-grey	
	4	158	Grey-blue	
	5	218	Clear grey	
	6	234	Greenish-white	
	7	259	Nearly pure white	
	8	267	Yellowish-white	
	9	275	Clear straw-yellow	
	10	281	Straw-yellow	
	11	306	Clear yellow	
	12	332	Bright yellow	
	13	430	Brown-yellow	
	14	505	Red-orange	
	15	536	Red	
	16	551	Deep red	
2nd	17	565	Purple	
	18	575	Violet	
	19	589	Indigo	
	20	664	Sky-blue	
	21	728	Greenish-blue	
	22	747	Green	
	23	826	Clear green	
	24	843	Yellowish-green	
	25	866	Greenish-yellow	
	26	910	Pure yellow	
	27	948	Orange	
	28	998	Bright orange-red	
	29	1101	Dark violet-red	
3rd	30	1128	Clear bluish-violet	
	31	1151	Indigo	
	32	1258	Greenish-blue	
	33	1334	Sea-green	
	34	1376	Brilliant green	
	35	1426	Greenish-yellow	
	36	1495	Flesh-colour	
	37	1534	Carmine-red	
	38	1621	Faint purple	

Colours of higher orders.

If the crystal C, Fig. 58, can be arranged as in the figure, so that the entire breadth of the quartz wedge Q does not overlap it, the bands of colour will be seen to be more or less faulted. If the axis of less elasticity in the crystal be parallel to the principal axis of the wedge, the bands of colour of the 2nd order will be faulted into or towards the region occupied by those of the 1st order, as shown in the case of the positive crystal C, Fig. 58; but if it be an axis of greater elasticity in the crystal that is parallel to the principal axis of the wedge, then colours of the 1st order will be faulted into the region of those of the 2nd order.

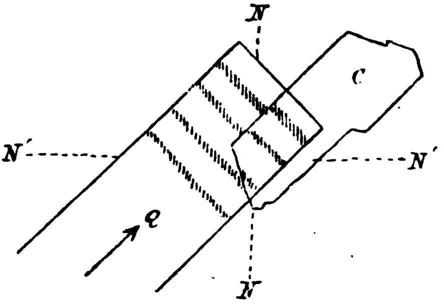

Fig. 58.

In this method of investigation, the ordinary eyepiece is used, and the condensing lenses above the polarizer are removed. The microscope is, in fact, arranged for parallel polarized light in the usual way. In convergent light, in the absence of a quartz-wedge, the ordinary Klein's plate may be made to serve the same end, by tilting it, either in the direction of the optic-axial plane (diagonal position), or at right angles to that direction. The positive or negative character of a bisectrix may also be determined in a very small and thin plate or scale of a mineral by focussing it in the microscope, (arranged for parallel polarized light, and with the ordinary eyepiece), by inclining a Klein's plate below the analyser in, or at right angles to, the direction of one of the axes of elasticity in the plate of the mineral. The position of the latter should be diagonal and, in very thin plates, the adjustment is best managed by first getting the crossed bars of the interference-figure in convergent light, and then rotating the stage 45°. The condensers are then removed from above the polarizer, and the ordinary eyepiece replaced. If, when the Klein's plate is inclined *in* the direction of the optic-axial plane of the crystal, the colours visible in the latter advance towards the centre, and then travel outwards towards the margin of the field, the bisectrix is positive; but if the colours first recede from the centre, and then advance inwards from the margin of the field, the bisectrix is negative.

In determining the optical sign of a uniaxial crystal, the best plan is to employ a mica plate, so thin that its use causes a difference of phase of a quarter-wave length. This, usually known as a quarter-undulation plate, may be either inserted in a slot above the objective of the microscope or a little below the eye-piece analyser. In a Norremberg's polariscope it is used in the latter position, and in any case the slot should be so arranged that the optic-axial plane of the mica plate can be inserted at an angle of 45° to the principal sections of the crossed Nicols.

If, when a section taken at right angles to the optic axis of a uniaxial crystal is placed in the field of the instrument, the mica plate be now inserted with its optic-axial plane at 45° to the arms of the cross in the interference-figure, one or other of the phenomena indicated in Figs. 59 and 60 will be observed.

In cases similar to that shown in Fig. 59, the cross separates into two hyperbolæ, which are resolved into two dark spots situated at their respective vertices; and these spots lie *in* the direction in which the optic-axial plane of the mica plate is inserted. In the quadrants of the interference-figure through which this plane passes, the segments of the rings appear to be pushed somewhat outwards, towards the margin of the field, so that they no longer correspond with the segments of the rings in the other quadrants. These phenomena are easily observed, and afford a ready means of recognising the *negative* character of a uniaxial crystal.

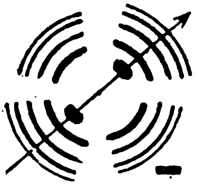

FIG. 59.

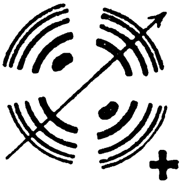

FIG. 60.

In the case of a positive crystal, the spots lie *across* the direction in which the optic-axial plane of the mica plate is inserted; and the segments of the rings situated in the quadrants on either side of this plane are displaced towards the margin of the field, as shown in Fig. 60.

The quarter-undulation plate may also be used for determining the optical sign of a biaxial crystal; but the results are not so satisfactory as those afforded by the quartz-wedge. It may, however, be as well to describe the mode of procedure. The polariscope is arranged for convergent light, the Nicols being crossed. The crystal-plate is then turned until the interference-figure lies in the *normal* position. The mica-plate is now inserted, with its optic-axial plane at 45° to the principal sections of the Nicols, so that it passes obliquely across the interference-figure. If the crystal be negative, the

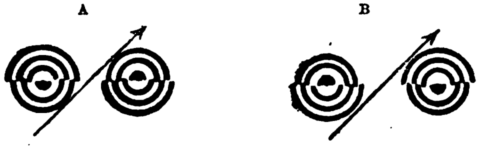

FIG. 61.

figure undergoes the alteration shown in Fig. 61 A, those portions of the rings in the upper left and lower right appearing larger than those in the lower left and upper right quadrants; in the latter quadrants two spots also appear, the left-hand one being below, and the right above, the horizontal line.

In positive crystals these phenomena are reversed, as shown in Fig. 61 B.

If again, the quarter-undulation plate be inserted with its optic-axial plane in the direction of the optic axial plane of the biaxial interference-figure, the latter being in the *diagonal* position, changes in the figure will ensue similar to those indicated in Fig. 62, where A represents a negative, and B a positive biaxial crystal. This method of testing the interference-figure in its diagonal position is, perhaps, preferable to the preceding, since it is easily remembered that in positive crystals the spots and enlarged segments of the rings lie towards the centre of the figure, while in negative crystals they are thrown towards the margin of the field.

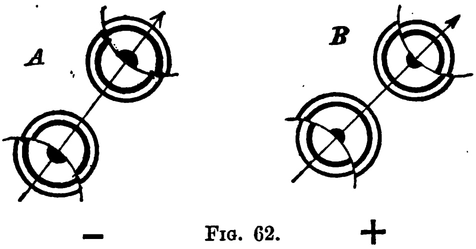

Fig. 62.

Biaxial crystals, in which the optic-axial angle is very small, approximate more or less closely to uniaxial crystals, as regards their interference-figures; and in such cases, the appearances of negative and positive crystals, when the quarter-undulation plate is used, resemble those shown in Figs. 59 and 60.

8. PLEOCHROISM.

Pleochroism, or the property which some crystals possess of exhibiting different colours when viewed in different directions, is only seen in those crystals which display a certain amount of colour. There are, however, colourless crystals in which this property can be demonstrated when colour has been imparted to them artificially. The phenomenon is due to selective absorption of rays of certain colours in definite directions, the absorption of the doubly-refracted rays in these directions being dissimilar.

Some crystals exhibit different colours or tints in three different directions. Such crystals are said to be trichroic. Trichroism is the most advanced phase of pleochroism known. If, from a crystal of Dichroite, *alias* Iolite, *alias* Cordierite, which crystallizes in the rhombic system, a cube be cut so that the three pairs of opposite faces are respectively parallel to the macro-, brachy-, and basal pinacoids, we shall see, on looking through those faces which are parallel to the macro-pinacoids, that the colour is greyish-blue; through the brachy-pinacoids the mineral will appear yellow; and through the basal pinacoids it will look indigo-blue. If the crystal be cut so that it can be looked through in directions other than these, mixed tints will be seen.

Other minerals exhibit only two colours when viewed in different directions, and these are said to be dichroic. The optically uniaxial crystals, when they possess colour, exhibit dichroism. Such crystals, if viewed in the direction of the optic axis, are found to display a different colour from that which is seen in all other directions at right angles to this axis.

A cylinder cut from a crystal of beryl so that its axis is parallel to the optic axis of the crystal, may, if viewed in the direction of the axis of the cylinder, appear sky-blue, while in all directions at right angles to this axis it displays a clear green colour. A mixed tint, resulting from the blue and green, is visible in intermediate directions.

The colours of the faces of a crystal seen by transmitted light are termed the *face-colours.* In Fig. 63 the rays of light traversing the crystal in the direction of the axis of least optical elasticity, 𝔠, vibrate in two directions at right angles to that axis, one set of vibrations lying in the plane of the axis of greatest elasticity, 𝔞, and the other in that of the axis of mean elasticity, 𝔟. In the same manner, light passing in the direction of the axis 𝔞 is resolved into vibrations in planes respectively parallel to the axes of elasticity 𝔟 and 𝔠; while rays travelling along 𝔟 vibrate in the planes of 𝔞 and 𝔠, as indicated by the small lettered arrows in Fig. 63. The face-colour of the face A is therefore determined by the axis-colours for 𝔟 and 𝔠; the face-colour of the face B depends upon the axis-colours for 𝔞 and 𝔠, while the face-colour C is compounded of the axis-colours for 𝔞 and 𝔟.

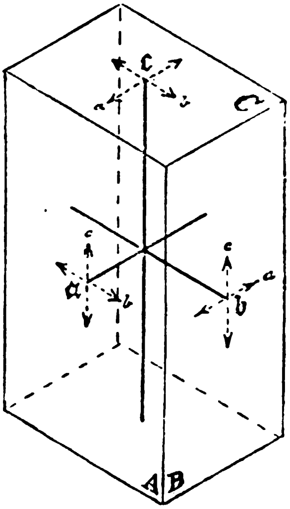

FIG. 63.

The axis-colours for any one direction may be separated and seen simultaneously by means of an instrument termed a dichroscope. They may also be separated, but cannot be seen simultaneously, by means of a single Nicol's prism. In this case the crystal, or section of the crystal, may be placed on the stage of the microscope, and, the analyser being removed, the polarizer is turned. The beam of plane polarized light which enters the crystal will at one point, in the revolution of the polarizer, vibrate parallel to one of the axes of elasticity, and the crystal will then exhibit the corresponding axis colour. If from this point the polarizer be turned 90°, the plane of vibration will then be parallel to another axis of elasticity, and the crystal will show a corresponding axis colour which will differ from that previously observed. By communicating a quick motion to the polarizer, the retina receives the impression of the two colours in rapid succession.

If, however, the crystal be too small to permit the employment of an ordinary Haidinger's dichroscope, and the observer wishes to compare the two axis colours side by side, he can do so by placing the crystal on the stage of the microscope, inserting a diaphragm with a very small aperture in the focus of the eye-piece, removing the polarizer, and placing a double-image prism over the eye-piece instead of the analyser. Two images of the aperture in the diaphragm will now be seen, one of which remains stationary while the other revolves round it when the double-image prism is turned. The former is the image formed by the ordinary, the latter that formed by the extraordinary ray; and the two images of the magnified crystal seen through the aperture will exhibit two axis-colours side by side.

Haidinger's dichroscope consists of a long cleavage-prism of Iceland-spar, C, Fig. 64, to the ends of which two glass prisms, *e*, *e*, each with a refracting angle of 18°, are cemented, for the purpose of rendering the doubly refracted rays parallel to the long edges of the prism. The latter is mounted in cork, and inserted in a brass tube, A, Fig. 64, about two-and-a-half inches in length. At one end of this tube a lens, B, is fitted, while a short length of tube, closed by a diaphragm D, in which a small square hole is made, slides into the opposite extremity.

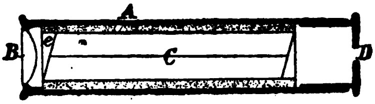

Fig. 64.

On looking through the instrument, two images of the square aperture are seen side by side; and, if the dichroscope be properly constructed, they should be in close juxtaposition.

To ascertain which image is formed by the ordinary and which by the extraordinary ray, the simplest plan is to hold the instrument with the principal section, or shorter diameter, of the prism vertically, and through it to examine the light polarized from a horizontal sheet of glass. Under these circumstances, the extraordinary image, *e*, Fig. 65, appears darkened, while the ordinary image, *o*, remains light, because the vibrations of the former lie in the plane of polarization, *i.e.*, in a plane at right angles to the surface of the glass plate; while the vibrations of the ordinary ray are parallel to those of the reflected polarized ray, which are at right angles to the plane of polarization. The directions of vibration in *e* and *o*, Fig. 65, are denoted by the small double-headed arrows.

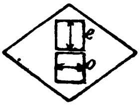

Fig. 65.

Having ascertained the directions of vibration in the two images, we are in a position to investigate the pleochroism of a crystal. If, for instance, we examine a crystal of common greenish hornblende, we may find the axis colour for rays vibrating parallel to the axis of least elasticity to be bluish-green, those parallel to the axis of mean elasticity brownish-green, and those parallel to the axis of greatest elasticity yellow.

The strength of the absorption may also be greater or less in the direction of any one of the axes of elasticity, and in this instance we note that the strongest absorption occurs for rays travelling in the direction of the axis of least elasticity, $\mathfrak{c}$, while rays passing in the direction of the axis of greatest elasticity, $\mathfrak{a}$, show the weakest absorption.

The absorption-scheme for this hornblende crystal is, therefore, $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$.

Among uniaxial crystals it is generally found that in those which are negative it is the ordinary ray which is the more strongly absorbed. Thus: in tourmaline the absorption is $o>e$, while in positive crystals it is usually the extraordinary ray which is more strongly absorbed.

Pleochroism may sometimes be found to be localized in a crystal around inclosures of other minerals. Such pleochroic spots and borders may be found in some crystals of Iolite, Andalusite, Biotite, Muscovite, etc.

Pleochroism may also be artificially induced in Olivine and some other minerals by heating thin sections of them to redness, for a minute or two, upon platinum foil.

Artificially staining a crystal will also, in certain cases, cause it to show pleochroism.

Crystals belonging to the cubic system never possess this property, nor can it be communicated to them, since their optical elasticity is similar in all directions.

The author is indebted to Mr. H. A. Miers and Mr. Grenville A. J. Cole for valuable assistance in the revision of several pages in Part I. Dr. F. H. Hatch and Mr. J. J. H. Teall have also kindly revised several pages in Part II.

PART II.

CHIEF ROCK-FORMING MINERALS.

HAVING rendered himself, to some extent, familiar with the general principals of mineralogical investigation, the student must next learn the leading characters which distinguish the more common rock-forming minerals from one another; and here, before employing the microscope, he must learn to use his eyes. The general information regarding these minerals, contained in an ordinary text-book, must also be in his possession before he will be in a fit condition to carry his inquiries further.

The number of mineral species which commonly constitute rocks, is comparatively small; and the following notes concerning them, as they occur in thin sections of rocks, may lessen the students' difficulty in recognising them.

The minerals are classified according to the systems in which they crystallize. Those of rare occurrence are not, as a rule, described.

CUBIC SYSTEM.

Native Iron.—Fe (*rare*). The presence of native iron in a dolerite from Ovifak in Greenland has been ascertained by MM. Fouqué and Lévy by treating an uncovered microscopic section of the rock with a solution of sulphate of copper, the surface of the iron becoming coated with a deposit of copper. In this particular instance the iron is associated with serpentine, and is considered to be of secondary origin.

Pyrites.—$Fe\,S_2$. The most common forms are the cube and the pentagonal dodecahedron, often in oscillatory combination, striation due to such combination being commonly seen on the faces of these forms.

In rock sections irregularly-shaped patches of pyrites are also of frequent occurrence; and the mineral is often altered into limonite or hematite, the hydrous condition being the more common. The change to limonite also takes place without any appreciable change in volume.

In thin sections pyrites is quite opaque; and consequently, when sub-stage illumination is employed, the mineral appears as black crystals or patches, which, under such circumstances, may be mistaken for magnetite or ilmenite, with both of which minerals pyrites is frequently associated. It may, however, be at once distinguished from them when viewed by reflected light, as it then presents its characteristic metallic lustre and brassy yellow colour, which may be distinguished from that of gold, the latter metal, when occurring in uncovered rock-sections, showing more or less deep scoring of its soft surface by the emery or other abrading material used in grinding the section. Minute quantities of gold in a rock are, however, best detected by chemical methods, such as Skey's, in which the powdered rock is roasted upon platinum foil and the gold dissolved by an alcoholic solution of iodine. A piece of filter-paper is then alternately moistened with the filtrate and dried, the ash of the paper after combustion exhibiting a purple or violet colour which is discharged on the addition of bromine water.*

Magnetite.—$Fe_3 O_4$. The common form is that of the octahedron. Such crystals are often twinned on a face of the octahedron, as in spinel. Octahedra of magnetite also very frequently exhibit parallel grouping, especially on the basal plane, as in artificially-formed crystals of alum, and in the naturally-formed crystals of some of the native metals, such as gold, copper, etc. It is not unusual in sections of eruptive

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* Crookes' "Select Methods of Chemical Analysis," 2nd edition. See also article by P. Holland, "*Chemical News*," vol. lvi., p. 271.

rocks, especially near their contacts, to find that this parallel grouping has resulted in the formation of skeleton crystals,

FIG. 66.

showing an arrangement similar to that indicated in Fig. 66. The mineral also very frequently forms irregularly-shaped patches in rock sections.

By sub-stage illumination magnetite looks black, and in the very thinnest sections it is always opaque. By reflected light it also exhibits a metallic lustre and appears black, and may thus be distinguished from pyrites; moreover, rocks containing magnetite cause a marked deflection of the magnetic needle; and polarity may not unfrequently be recognised by the repulsion of the needle at one point in a specimen and its attraction at another. Ordinary pyrites, on the other hand, exerts no influence upon the magnetic needle. The presence of magnetite in a rock may also be ascertained by crushing a small fragment of it, and rubbing a perfectly clean and dry magnetized knife-blade, or bar, in the powder, when any magnetic particles present will adhere to the blade or bar. This also serves to distinguish it from ilmenite, graphite, chromite, etc. Magnetite sometimes becomes altered into hematite (Martite), and more frequently into limonite. Titanic acid is often present in the mineral. Magnetite is one of the most common constituents of eruptive rocks.

Chromite.—$Fe\ Cr_2\ O_4$ (*when pure*). Mg and Al generally present. Crystals usually octahedra, less often cubes; but the mineral more commonly occurs in irregularly-shaped grains and patches. In very thin sections chromite is translucent, and shows a brown or reddish-brown colour when seen by transmitted light; and the surfaces of the sections appear very irregular and rough, owing to the high refractive index of the mineral. The crystals are often traversed by irregular cracks, but show no distinct planes of cleavage.

By reflected light chromite exhibits a feeble metallic lustre, and a black or greyish-black colour. Grains of chromite are often superficially altered into a greenish substance, which is probably chrome ochre.

Chromite occurs most frequently in rocks rich in magnesia, as in certain olivine-bearing rocks (Lherzolite, Dunite, etc.), and especially in Serpentines.

Spinel,—$Mg\ Al_2O_4$,—crystallizes in octahedra, very commonly twinned on a face of the octahedron. There are several varieties of this mineral, in which the chemical composition differs, owing to isomorphous substitution, sometimes of the protoxides, but generally of the sesquioxides.

Ordinary spinel appears reddish, or colourless by transmitted light; and the surfaces of sections look rough, owing to the high index of refraction.

When spinels occur in octahedra in rock sections, they generally have sharply-defined boundaries, and they sometimes contain fluid lacunæ.

Pleonaste is a black variety of spinel, which contains protoxide of iron and magnesia, together with sesquioxide of iron and alumina. By transmitted light it appears green, by reflected light, black.

Hercynite,—$Fe\ Al_2\ O_4$,—and *Gahnite,* or zinc spinel $(Zn\ Mg)\ Al_2\ O_4$, are also translucent and green when seen by transmitted light in thin sections, and are only to be distinguished chemically.

Picotite, or chromium spinel, is occasionally met with as a rock-constituent, notably in lherzolite, and some other rocks rich in olivine. In these it most frequently occurs in irregular grains, which, in thin section under the microscope, are translucent, and of a deep brown or coffee côlour, and often resemble drops of glue which appear to have been irregularly smeared over the slide.

Garnet Group.—The garnets constitute a very well-marked group, having the general formula $R_3 \bar{R}$, $Si_3 O_{12}$, in which R may be Ca, Mg, Fe, or Mn, while $\bar{R}$ is Al_2, except in Andradite, where it is Fe_2, and in Ouwarowite Cr_2. The habit is generally dodecahedral, as is also the cleavage. The sections, as seen in microscopic slices of rocks, are usually hexagonal, octagonal, or square when well-formed crystals are present; but it is extremely common to find that the garnets in a rock occur in rounded, and sometimes very irregularly-shaped, grains or aggregates of grains. The crystals and grains are often traversed by irregular cracks.

The garnets commonly met with in rocks are, as a rule, perfectly isotropic, remaining quite dark during complete rotation between crossed Nicols; but occasionally they exhibit anomalous optical properties which have been the subject of much careful investigation.

The peculiar structure of some crystals of garnet is considered by C. Klein to be the principal cause of these optical anomalies, and he divides the doubly-refracting garnets into four groups. Of these the rhombic dodecahedral type is the one most commonly met with in those rock-forming garnets which show double refraction.

The most marked examples of this type have hitherto been found at Auerbach and Jordansmühl, in Saxony; and these crystals appear to be built up of twelve hemimorphic rhombic pyramids, *i.e.*, of forms consisting of four pyramidal faces and one basal plane. The basal plane of each hemimorphic pyramid corresponds with one of the faces of the rhombic dodecahedron, while the pyramids all terminate in the centre of the crystal, as indicated in Fig. 67, where one of these pyramids is supposed to be removed, the impressions of the four pyramidal faces being marked II., III., IV. and V., while on the dodecahedral faces of the composite crystal the basal planes of its individual components are marked with I. If a section be made parallel to a face of the rhombic dodecahedron, as indicated at A, Fig. 68, it will be seen, in plane-polarized light, to be composed of four narrow marginal areas bordering a central rhomb, in which, by convergent light, a biaxial interference-figure may be detected, so situated that the optic-axial plane is parallel to the longer diameter of the rhomb (*i.e.*, of the base of the hemimorphic rhombic pyramid), the bisectrix being normal to the rhomb face, as indicated in Fig. 69.

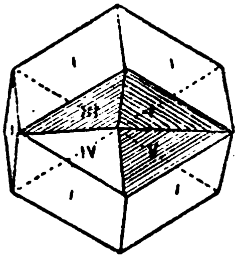

Fig. 67.

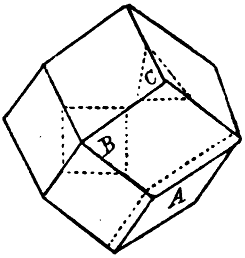

Fig. 68.

If, again, a section be made parallel to a face of the cube, as at B, Fig. 68, it will be seen in plane polarized light to break up into four fields; the two directions of maximum extinction being respectively parallel and at right angles to the edges of the section, while in convergent light each field shows an interference-figure, as indicated in Fig. 70. A section taken parallel to a face of the octahedron, as at C, Fig. 68, will exhibit three distinct areas, as in Fig. 71, where the directions of maximum extinction in each field are shown by the arms of the small crosses.

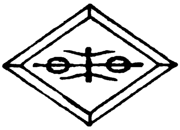

FIG. 69.

FIG. 70.

FIG. 71.

Finally, a section bisecting two opposite faces, and following four polar edges, will result in a hexagon, which, in parallel polarized light, shows six triangular fields, the directions of extinction in each being parallel and at right angles to the base of the triangle, as indicated by the crosses in Fig. 72.

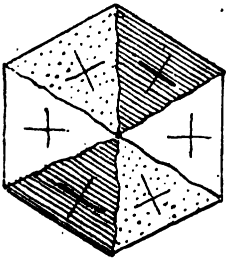

FIG. 72.

A description of the less common types of doubly-refracting garnets will be found in the last edition of Rosenbusch's "Mikroskopische Physiographie."

Garnets frequently exhibit a zoned structure, which in thin sections is sometimes denoted by differences in colour, the zones probably differing in chemical composition, through various grades of isomorphous substitution; or at others the zones will be seen, in parallel polarized light, to be alternately isotropic and anisotropic.

So far as the microscopic characters of the different species are concerned, *Almandine* in thin sections is either red, or in very thin ones colourless. It frequently occurs in irregular grains, as well as in crystals. The latter often contain cavities of the same form (negative crystals), also fluid lacunæ, and occasional inclusions of rutile, quartz, etc. *Grossular* usually appears colourless in microscopic sections. It is at times rich in inclusions of other minerals, and fluid lacunæ are often present. *Common garnet* in thin sections may be colourless, or various shades of reddish-brown and yellowish-red. It frequently has a zoned structure, and often passes by alteration into chlorite and hornblende. Occasionally it exhibits double-refraction. Fluid lacunæ and other inclosures are common. *Melanite* appears of various shades of deep brown when viewed in thin section by transmitted light.

Spessartine, or manganese-alumina garnet, occasionally exhibits a red, or yellowish-red colour; but in the Belgian hone-stones, of which it is an important constituent, it occurs mostly in granules of very small dimensions, which are almost colourless. Altered conditions of this garnet have not been observed. Large crystals are found in quartzite near Bastogne, in the Ardennes, which contain inclusions of quartz and mica, arranged somewhat in the manner of the inclusions in Andalusite.

Pyrope, or magnesia-alumina garnet, usually containing some chromium and protoxide of iron, occurs chiefly in serpentines and rocks rich in olivine, always in rounded or angular grains. Crystals of pyrope are not known. In thin sections, by transmitted light, it exhibits various shades of red, according to the thickness of the section. The grains of pyrope are sometimes seen to be surrounded by a coating of a pale greyish-brown substance, which is an alteration product, and has been named Kelyphite by Schrauf; but its precise constitution is not yet known. Becke has described similar alteration-products as consisting of a mixture of picotite, or chrome-spinel, with probably hornblende. The kelyphite zones have a radial structure.

Leucite,—$K_2\,Al_2\,Si_4\,O_{12}$,—was originally regarded as a cubic mineral, until G. vom Rath described it as crystallizing in the tetragonal system.

The anomalous optical properties which leucite crystals commonly exhibit were first recognised and discussed by Brewster, and of late years they have been the subject of much research. The mineral has not merely been referred to the cubic and to the tetragonal, but also to the rhombic and monoclinic systems. Some observers have found its double refraction to be positive, others negative. Crystals of leucite have the form of icosi-tetrahedra. In parallel polarized light sections of these crystals show twin lamellation (frequently parallel to faces of a rhombic dodecahedron, unless of very small dimensions, when they appear isotropic), and display more or less double refraction. To describe the directions followed by these lamellæ and their relation to the existing or possible faces of the crystal, is beyond the scope of this work. The general conclusion at present is, that the lamellar structure and the double refraction of leucite should be attributed to conditions of unequal tension existing within the crystals, as we usually see them; for the recent investigations of Klein, and subsequently those of Penfield, show that at a temperature of 500° C. they revert to a condition of perfect isotropy.

The double refraction of the mineral is weak, and is imperceptible in very thin sections, unless a Klein's plate or a quartz plate cut parallel to the optic axis, and of such thickness as to show the *teinte sensible*, be employed.

Inclusions of olivine, apatite, and other minerals, especially augite, are common in leucite crystals; and they are frequently seen to have a definite arrangement, being sometimes grouped about the centre of the crystal, at others ranged in concentric zones; glass-inclosures, gas-bubbles, and occasionally fluid lacunæ being also present.

By ordinary transmitted light, sections of leucite appear colourless. In polarized light the colours are weak, even in moderately thick slices. Leucite very commonly becomes altered into analcime. This alteration-product often shows a finely fibrous structure, which is attributed by several observers to the further alteration of the analcime into a mixture of felspar and mica, of which the felspar may ultimately pass into kaolin.

Leucite is a mineral of very restricted distribution, the districts in which it mainly occurs being the Papal States, where it is very plentiful, the Eifel, and rather sparingly in a few other localities, one or two being in the United States. It is found only in volcanic rocks.

Analcime,—$Na_2\ Al_2\ Si_4\ O_{12}$,—occurs in icosi-tetrahedra, similar to those of leucite. It is usually found either filling small cavities and fissures, or pseudomorphous after other minerals, especially after nepheline and leucite. The refractive index is low, being 1·4874 for red light. Anomalous double refraction is common in this mineral; and, as in the case of leucite, is now usually referred to conditions of tension. By strongly heating sections of analcime in steam, they become, according to C. Klein, perfectly isotropic. If, however, the heating be carried on in a dry atmosphere, the mineral loses water, and the double refraction becomes more pronounced.

On heating the section slightly, so that no loss of water occurs, the double refraction, thus augmented, again diminishes as the temperature is lowered; but when the water has been expelled by strongly heating the section, lowering of temperature then produces no effect, the increased double refraction brought about by this process remaining constant. A high temperature, engendering loss of water, also causes the section to lose its transparency to a greater or less extent. Analcime is never a normal rock-forming mineral, but is always of secondary origin. It is a constant constituent of the rocks termed Teschenites (from Teschen in Austria), and is also very common in basalts. It is likewise met with in the Elœolite-Syenites and the Phonolites.

Sodalite.—$2(Na_2 Al_2 Si_2 O_8) + Na Cl$. The common form is that of the rhombic-dodecahedron, sometimes in combination with the octahedron. The crystals are frequently twinned, like spinel, upon a face of the octahedron. It is not usual, however, to meet with well-formed crystals, although such do occur in some of the syenites of Greenland, the foyaites of Portugal, in certain phonolites and trachytes, and especially in some of the Vesuvian lavas. The cleavage of sodalite is parallel to faces of the rhombic-dodecahedron, but it is seldom well-shown in microscopic sections of crystals which have not been formed in cavities.

By ordinary transmitted light sections of sodalite appear of a pale bluish, greenish, yellowish, or occasionally of a pink colour.

The mineral is almost invariably quite isotropic; and when any double refraction has been observed in it, it has always been in the immediate neighbourhood of inclusions.

The index of refraction is low, that observed in sodium light ranging from 1·4827 to 1·4858. Inclusions of other minerals, such as nepheline, augite, etc., are met with in sodalite, which also, at times, contains gas-bubbles, glass inclosures, and fluid lacunæ. Sodalite mostly occurs in rocks of a syenitic character.

Haüyne (Nosean). The minerals haüyne and nosean are very closely related, being isomorphous mixtures of

$2(Na_2 Al_2 Si_2 O_8) + Na_2 SO_4$, and $2(Ca Al_2 Si_2 O_8) + Ca SO_4$.

Of these two formulæ the first may be taken as that of the Nosean type, while the Haüyne type may be represented by

$$\begin{cases} 2(Na_2\,Al_2\,Si_2\,O_8) + n\,Na_2\,SO_4 \\ 2(Ca\,Al_2\,Si_2\,O_8) + m\,Ca\,SO_4 \end{cases}$$

Both minerals are soluble in hydrochloric acid, with gelatinization. The solution on drying gives microscopic monoclinic crystals of selenite (Fig. 73), when haüyne has been dissolved, while in the case of nosean very few or no selenite crystals are formed, owing to the total, or almost total, absence of lime in nosean. The acid employed should not be too strong, nor the temperature at which the evaporation is conducted too high, otherwise rhombic crystals of anhydrite will be formed instead of monoclinic ones of selenite. Haüyne is usually of a bright blue or greenish-blue colour, but it is sometimes reddish or greyish. Nosean is usually grey, sometimes bluish-grey, greenish, or blackish-brown. The colours of these minerals, however, undergo change when they are heated, or, if colourless, they assume colour. Heated in sulphur vapour, they become blue.

FIG. 73.

Haüyne and Nosean in thin sections appear clear and colourless, except where they exhibit dark zones. Between crossed Nicols they are, as a rule, perfectly isotropic; but instances of anomalous double refraction are occasionally observed.

Haüyne and Nosean always occur in crystals which are either sharply defined in sections, as six-sided figures, squares, or rectangles, or as rounded crystals. They usually contain fluid lacunæ, glass inclusions, and gas bubbles, as well as large numbers of microliths. These are generally arranged in definite ways (Fig. 74), sometimes forming zones. Within these areas the microliths and other inclusions are often found to lie in directions parallel to the octahedral axes (*i.e.* the axes of ternary symmetry, which are normals to the faces of the octahedron). Sections, therefore, which are parallel to faces of the octahedron show three systems of striæ, formed by the linear arrangement of the microliths and other inclusions, these three systems crossing at 60°, while sections parallel to faces of the cube and of the rhombic-dodecahedron show two sets of striæ, crossing at right angles to one another. Minute scales of specular iron are also at times present in these crystals, and, as pointed out by Rosenbusch, frequently lie in the planes of dodecahedral cleavage, and have probably been formed at a later period than the crystals of haüyne.

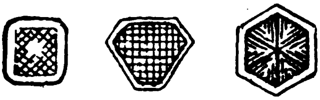

FIG. 74.

The alteration which haüyne most commonly undergoes is brought about by the removal of the molecule containing sulphur, and by a gain of water, the result being usually natrolite, or occasionally some other zeolite. Calcite is likewise formed now and then from the alteration of haüyne, and limonite is sometimes found pseudomorphous after both haüyne and nosean.

These minerals occur very plentifully in many phonolites, leucitophyrs, etc. They are, in fact, generally associated with the minerals nepheline and leucite, and may be looked for in the volcanic rocks in which either of those minerals happen to form essential constituents.

Perowskite,—$CaTiO_3$,—is another cubic mineral sometimes met with in rocks containing nepheline or leucite. The common forms are the octahedron and cube, or combinations of them. The crystals,—which by transmitted light range from greyish to brownish-yellow and reddish-brown,—often form aggregates. They are of purely microscopic dimensions, ·02 to ·03mm., seldom larger. They have a high refractive index, and, consequently, the surfaces of the sections appear very irregular. The larger crystals show double-refraction, which is considered to be due to conditions of tension, the smaller crystals show none. To distinguish this mineral with certainty from spinel, chromite, etc., recourse must be had to chemical analysis.

There are a few other cubic minerals which occasionally occur as constituents of rocks, but they are, from this point of view, comparatively unimportant.

Fluorspar,—CaF_2,—never occurs as an essential rock-constituent but is occasionally met with in irregularly-bounded grains in rocks of a granitic, syenitic, and gneissic character. It is, however, an exceptionally noticeable constituent of certain boulders at Trowlesworthy Tor in Devonshire, associated with microcline, schorl, etc. Sections of fluorspar generally show sharply-defined octahedral cleavage planes, and very frequently contain fluid lacunæ. The mineral, when in thin sections, usually appears colourless or violet. The colour is due to the presence of some hydrocarbon compound, and may be discharged by heating. When heated in a glass tube with microcosmic salt, hydrofluoric acid gas is evolved, and the glass becomes corroded. The refractive index is very low, and serves to distinguish it from most rock-forming minerals.

HEXAGONAL SYSTEM.

From the foregoing descriptions it will have been seen that the highest type of symmetry is not always accompanied by those optical properties which theory demands. Circumstances frequently compel many of the crystals belonging to the cubic system to abandon their isotropy. We know that in most cases crystallization is accompanied by contraction — in some few, by expansion. In the former instance, tension results *within* the crystal, through the attraction which draws together the molecules from the chaos of amorphism to the order of crystallization; in the latter, strain results from resistances *without* the crystal in the matter which surrounds it. It becomes, then, a question between opposing forces; and, when the matter surrounding a crystal crystallizes, the relative co-efficients of expansion or contraction are important factors. The results of contraction and those of compression are the same, but, apparently, with this exception, that, in the former case, the molecular spacing, and corresponding density of the intermolecular æther, is wholly dependent upon the attractions and repulsions which the molecules of the crystals exercise upon one another; while, in the latter, forces external to the crystal are brought to bear upon it, and their action is only modified by the resistance which the molecular spacing of the crystal (*i.e.*, the repulsions exercised between its molecules) and the relative inclination of its developed faces to the directions of compression may be able to offer. In such a case, therefore, the results of compression may be very unequal and irregular; and the same may be said in instances where contraction instead of compression has troubled a crystal during or after its birth, especially if the latter have occurred at a high temperature, since it may be readily imagined that the unequal thermal conductivity along different directions in the different minerals which frequently surround a rock-forming crystal, would more or less affect the readiness with which that crystal will cool in given directions at a given time. Under such circumstances, a crystal may undergo irregular changes in its molecular spacing sufficient to produce an appreciable change in its angles, so that a cubic crystal may ultimately resemble one of lower symmetry.

In the hexagonal system, as in all the others of lower symmetry than that of the cubic, the crystals are anisotropic. Those of the hexagonal system are optically uniaxial, as already mentioned. The optic axis coincides with, or is parallel to, the principal crystallographic axis; and it may also be the axis of greater or of lesser optical elasticity. In the former case, the double-refraction is negative; in the latter, positive. Crystals belonging to this system, where they possess colour, exhibit phenomena of dichroism.

In convergent polarized light basal sections, both of hexagonal and tetragonal crystals, sometimes show anomalous optical characters—when the preparation is turned, the cross of the interference-figure opening out into hyperbolæ, as in the case of a biaxial crystal in which the optic-axial angle is small. On moving such a section across the stage, however, the interference-figure usually exhibits changes, the seeming axial angle increasing in one spot, diminishing in another, the pseudo axial plane suddenly jumping into another position, or the figure reverting to the usual circular rings and cross proper to a uniaxial crystal. If we examine such a section in parallel polarized light, we shall generally find evidence of twinning or of strain to account for these abnormal phenomena.

Graphite,—C,—is chiefly met with, as a rock constituent, in slates and shales, and occasionally in old crystalline schists and gneiss. It seldom appears in well-formed crystals, but usually in irregular grains and scales, and often as fine dusty matter. The crystals give hexagonal or rounded discoidal sections parallel to the base, and rectangular ones in directions at right angles to the basal section.

Graphite is opaque; it has a metallic lustre, and, by reflected light, appears black or brownish-black. If present in tolerable quantity in a rock, the latter, if its planes of cleavage or schistosity be rubbed over white paper, will soil it, as if with ordinary pencil dust. It should, however, be remembered that molybdenite and manganese oxides also soil paper; but a little of the powder scraped from the rock, and submitted to the usual blowpipe tests will generally give the information required.

Hematite,—Fe_2O_3,—is met with, as a rock constituent, either in the earthy condition known as reddle, or raddle, or in the crystalline state. In the latter, it occurs in rhombohedra usually much flattened, the basal planes predominating, and forming six-sided tables, the faces of rhombohedra appearing only on their edges. Such crystals, from their brilliant metallic lustre, are known as specular iron, or iron-glance. When the crystals are extremely thin, they come under the denomination of micaceous-iron, or iron-mica (*eisen-glimmer*). They are then translucent, and appear of various shades of red, orange-red, or reddish-yellow by transmitted light. In the earthy condition the mineral is opaque when in films of any appreciable thickness; but such feebly coherent matter usually disappears from a rock section in the process of grinding. When lying in very thin films, or in a state of fine separation, within the minerals constituting the rock-section, it appears merely as a pigment, forming more or less translucent rusty stains.

Crystals of iron-glance, too thick to be termed micaceous, are opaque, and, by reflected light, they exhibit a metallic lustre and appear black or greyish-black, but show a somewhat reddish tint, or, where scratched, a bright red earthy, reddle-like streak.

Turgite, however, which has the composition $2\ Fe_2O_3H_2O$, also gives a red streak.

Hematite is a common constituent of many rocks, and frequently forms pseudomorphs after pyrites, olivine, garnets, and other minerals. Through weathering, the iron, which often exists in a rock in the state of protoxide, becomes converted into sesquioxide, staining the rock red, especially in the vicinity of joint-planes.

Beautiful microscopic crystals of micaceous hematite may be procured by dissolving a small fragment of Carnallite, the hydrous chloride of potassium and magnesium found at Stassfurt, which owes its colour to these minute crystals.

Ilmenite,—$Fe\ TiO_3$,—occurs very commonly in eruptive rocks, either in rhombohedral crystals, which usually have a tabular habit owing to the development of the basal planes, or in irregularly shaped grains and patches, which may frequently be mistaken for magnetite, since they are opaque, black, and have a metallic lustre.

Ilmenite also occurs in very thin translucent tabular crystals of a pinkish-brown colour by transmitted light, which bear the same kind of relation to the larger crystals that micaceous hematite, or iron-mica, does to iron-glance or specular iron. These micaceous crystals of ilmenite are sometimes termed titaniferous iron-mica. The mineral also occurs in an earthy or ochreous condition.

Sections of perfectly fresh ilmenite crystals commonly show traces of a laminar structure parallel to faces of the rhombohedron, $\pi\,(10\bar{1}1)$; and when decomposition has taken place within the crystal it generally follows these planes. The decomposition-product, which is termed leucoxene, is a granular substance which usually appears opaque, or nearly so, although in extremely thin layers it has been seen to exhibit strong double-refraction. By reflected light, leucoxene is white, sometimes with a yellowish or brownish stain. In a crystal, therefore, which shows incipient decomposition, we see, by reflected light, alternating white and black bands, lying parallel to the faces of the rhombohedron, the former consisting of leucoxene, and the latter of unaltered ilmenite. Sometimes the decomposed areas appear irregular; and, when the entire crystal is decomposed, nothing but a white or yellowish-white pseudomorph of leucoxene remains. The presence of this decomposition-product will frequently serve to distinguish ilmenite. Considerable diversity of opinion has existed concerning the precise nature of leucoxene, but it is now regarded either as sphene or anatase. The brownish or yellowish colour which leucoxene sometimes displays has been found by Cathrein to result from a mechanical admixture of rutile (sagenite), the latter mineral originally occurring in the ilmenite. Similar microscopic intergrowths of sagenite with specular iron have also been observed.

Ilmenite occurs in granites, syenites, diorites, basalts, and many other eruptive, as well as gneissic rocks.

Calcite,—$Ca\,CO_3$,—occurs in rocks, chiefly in the condition of crystalline-granular aggregates and crystalline grains of irregular shapes. These, however, constantly show, especially in parallel polarized light, a twin lamellation parallel to faces of the rhombohedron $-\frac{1}{2}R$ or π $(01\bar{1}2)$. A similar structure may be artificially produced in calcite, as shown by Reusch's well-known experiment, which consists in pressing the edge of a knife blade into a cleavage-prism of Iceland spar in a direction at right angles to one of the long edges formed by the faces containing one of the obtuse angles of the prism.

It is now very generally admitted that this twin-lamellation, which can be well seen in any section of crystalline limestone or marble, has resulted from pressure, a conclusion which is strengthened by the occasional curvature of the lamellæ.

In most instances calcite is transparent or translucent and colourless; but it is sometimes stained by other substances, so that the range of colours which may be presented by calcite is considerable, and occasionally it may appear almost opaque.

The double-refraction is extremely strong, and negative. Owing to the general absence of colour in this mineral, it does not often exhibit dichroism; but a difference in the absorption of light is easily to be recognised in most microscopic sections by removing the analyser and rapidly turning the polarizer, the ordinary ray showing the stronger absorption. Similar difference of absorption may likewise be detected in sections of dolomite and magnesite. These minerals also show cleavage planes, parallel to faces of the rhombohedron, similar to those seen in calcite; but this strongly-marked cleavage, although very characteristic of sections of these minerals, affords no means of distinguishing them from one another.

In limestones of oolitic character, the small spherical crystalline aggregates show a radial and generally a concentric zonal structure, and exhibit a dark cross when viewed between crossed Nicols in parallel polarized light. Fluid lacunæ and enclosures of other minerals, usually also carbonates, are common in calcite.

Apart from those sedimentary rocks in which calcite is an essential constituent, its occurrence in others, notably in veins and as a cement in breccias and tuffs, whether of pyroclastic origin or not, is very frequent; and it is also one of the most common occupants of the cavities which are so plentiful in many lavas, the amygdaloids, when not chalcedonic or zeolitic, being generally calcareous. In all such cases the calcite must, as a rule, be regarded as a product of secondary origin, resulting from the infiltration of water holding bi-carbonate of lime in solution. In some instances, however, it must be attributed more or less directly to the decomposition of silicates containing lime; and it is probable that in eruptive rocks the calcite which they contain is due to this cause.

Pseudomorphs of calcite after triclinic felspars, especially those rich in lime, are often met with; and these, together with pseudomorphs after other lime-bearing minerals, result from the alteration of the minerals themselves. In other cases, as in that of calcite after olivine, we have examples of pseudomorphism by replacement.

Dolomite,—$\text{Ca CO}_3+\text{Mg CO}_3$,—as already mentioned, resembles calcite closely in some respects.

As a rock constituent it nearly always assumes definite crystalline form (that of the rhombohedron R or π $(10\bar{1}1)$. The importance of this almost universal tendency of dolomite to develop its crystalline faces, is emphasized by Renard as a means of distinguishing this mineral from calcite. Even in the most compact aggregates of dolomite, we do not find that they consist of irregularly-shaped crystalline grains, as in most limestones composed of calcite, but of more or less perfectly developed rhombohedra. Moreover, owing to the absence of twinning, the lamellation so common in calcite has never yet been observed in dolomite. The rhombohedral cleavage in the latter mineral is as strongly marked as in calcite.

On treating an uncovered section, containing dolomite, with dilute hydrochloric acid, the dolomite will be only feebly attacked *in the cold,* while calcite, under similar circumstances, would dissolve rapidly, and with brisk effervescence. Another point in which crystals of dolomite differ from those of calcite, is in the strong curvature of the faces often seen in the former. An isomorphous substitution of protoxide of iron for the protoxide-bases present in dolomite, is very common and very variable; and the minerals of this series consequently show considerable diversity in specific gravity, colour, etc.

Apatite,—$3\ \text{Ca}_3\,\text{P}_2\,\text{O}_8+\text{Ca}\ (\text{Cl},\ \text{Fl})_2$,—is a mineral of frequent occurrence in a large number of rocks; indeed, there are few of eruptive origin which do not contain some apatite. In microscopic sections of rocks it generally appears in the form of minute needle-like hexagonal prisms, usually, but not invariably, much elongated in the direction of the principal or optic axis. Transverse sections of such prisms show sharply-defined hexagonal outlines and, between crossed Nicols, appear perfectly dark during a complete rotation. Sections parallel to the principal axis undergo extinction when that axis is parallel to the principal sections of one or other of the Nicols. The prisms are usually combined with basal pinacoids, but occasionally with pyramids. In some of the crystalline schists, apatite occurs in rounded or oval grains, which, however, in cross section, give hexagonal figures. As a rule, the mineral is transparent and colourless or yellowish, occasionally bluish or brownish. The double refraction is negative and weak. The absorption for the extraordinary is greater than that for the ordinary ray. The coloured varieties are often strongly dichroic, but the colourless, of course, only show an unequal absorption for *o* and *e*, which is perceptible even in small crystals. The interference-figures afforded by basal sections of apatite in convergent polarized light, are usually very irregular.

To detect apatite chemically in a rock, it is often necessary to operate upon a tolerably large sample, as the crystals have a tendency to mass themselves together in certain spots.

The usual molybdate of ammonium reaction, which gives a yellow crystalline precipitate, is the most satisfactory, while dilute sulphuric acid, added to another portion of the solution, will yield microscopic crystals of selenite. In spite of the ease with which apatite may be decomposed in the laboratory, it is, nevertheless, one of the last minerals which usually succumbs to weathering.

Inclusions of fluid and of gas are common in crystals of apatite. This mineral is generally found in greater quantity in the basic than in the highly-silicated eruptive rocks.

Quartz,—$Si\,O_2$,—is one of the commonest and most important of the rock-forming minerals. The crystals are either well-developed combinations of the prism ∞ R and pyramid + and − R or, more rarely, are represented by the pyramid only. It is usual to find considerable irregularity in the development of the faces, and rounded forms are very common. The latter often show signs of corrosion, which, when far advanced, has produced deep inlets or creeks in the crystal, into which the surrounding magma or molten rock-substance has entered, forming finger-like or bulbous intrusions, frequently constricted near their entrances.

Intimate intergrowths of quartz with felspar are sometimes met with, giving rise to what is known as micropegmatitic structure.

It is, however, common to find that the quartz, in crystalline rocks, occurs in irregularly-shaped grains, which show little or no indication of definite crystalline forms.

Quartz, when free from inclosures of coloured minerals, appears clear and colourless in thin sections; and any turbidity or milkiness which a crystal may exhibit, is generally found, under the microscope, to be due to the inclusion of numerous fluid lacunæ. These are usually of quite microscopic dimensions, the very small ones frequently showing spontaneous movement of the bubbles, while the larger ones occasionally contain not merely water, but also liquid carbonic dioxide,

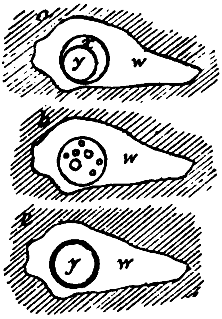

Fig. 75.

which latter assumes the gaseous condition when the section is heated to between 31° and 32° C.

In Fig. 75 *a*, such a fluid lacuna is shown, *w* representing the water, *x* the liquid carbonic dioxide, and *y* a bubble of carbonic dioxide gas. When heated to the critical point, the appearance shown in Fig. 75 *b* will be visible for a second or two. This apparent ebullition is due to the vaporization of the liquid carbonic dioxide, which, when complete, gives rise to one large gas bubble, as shown at *y*, Fig. 75 *c*.

In Fig. 75 *a*, it will be seen that the liquid carbonic dioxide adheres to the water-surface, in preference to the wall of the cavity. The shading in the figures denotes the surrounding quartz. Minute crystals of rock-salt are also occasionally met with in the fluid inclosures in quartz.

The refractive index of quartz has been found, in sodium-light, to be 1·5441 for the ordinary, and 1·5532 for the extraordinary ray. The double refraction is positive and weak. Moderately thick sections of quartz show brilliant colours in parallel polarized light. In convergent light they also give, in basal sections, the characteristic interference-figure, over the centre of which the arms of the dark cross do not extend. In thin sections, however, the interference-rings are not visible, but merely the dusky cross, now showing the intersection of the arms, which does not appear in thick sections.

The optical sign may also be recognised even in the extremely thin basal plates.

In parallel polarized light the colours displayed by very thin sections are restricted to the first order of Newton's scale.

In sections of crystalline schists, the quartz frequently occurs in elongated, lenticular, or fusiform grains, which often show indications of irregular strain when examined in polarized light. In such rocks it is also by no means uncommon to find the fluid enclosures ranged in more or less parallel lines, which, in aggregates of quartz-grains, may be seen to follow the same direction through a great number of consecutive grains, quite irrespective of their optical orientation. This phenomenon may, as a rule, be regarded as the result of pressure which the rock has undergone, the lines of inclosures running at right angles to the direction of pressure. At times two or more systems of these parallel, or approximately parallel, lines may be traced in the same crystals, indicative of stresses in more than one direction.

Tridymite,—Si O_2,—differs from quartz in its specific gravity, which ranges from 2·28 to 2·33, while that of quartz is 2·65. Tridymite also differs from quartz in its habit and twinning, and in being soluble in a boiling solution of carbonate of soda. It has been referred to various crystallographic systems, but is generally regarded as hexagonal. The crystals are always small. The cleavage is basal. Through the feeble development, or almost complete suppression of one pair of the prism faces, the crystals often look like rhombic forms. They are colourless and translucent, and possess positive double refraction. In rock sections, however, the mineral occurs in aggregates, which, owing to the overlapping of the crystals, somewhat resemble fish-scales, the basal plane of one crystal overlapping that of another; and these basal sections, or rather scales, appear perfectly isotropic, while scales lying in other directions show feeble double-refraction.

The larger crystals have, however, been found to depolarize in a peculiar manner when viewed normal to the base in parallel polarized light, while, in convergent light, the interference-figures are suggestive of those of biaxial crystals. It has been inferred that the optical properties of tridymite are anomalous, Merian having found that the mineral becomes isotropic when heated and viewed in parallel polarized light in a direction normal to the basal planes, while, still viewed in this direction, it reverts on cooling to its anisotropic condition. The conclusion is, therefore, that the crystals of tridymite are in a condition of abnormal tension, generated during their passage from the high temperature at which the tridymite-bearing volcanic rocks were formed to the much lower temperature attained by those rocks on cooling.

For an account of the peculiar twinning or trinning of tridymite, the student should consult the larger text-books.

Tridymite is essentially a volcanic mineral, occurring chiefly in rocks of a trachytic character, as in the trachytes of the Drachenfels on the Rhine, of Mont D'or in the Auvergne, of Tardree in Co. Antrim, Ireland. It has also been observed in Augite-andesites.

Chalcedony,—SiO_2,—has a specific gravity of 2·59 to 2·64, rather lower than that of quartz, and somewhat higher than that of tridymite. It is usually regarded as a mixture of quartz and amorphous silica.

Chalcedony is of common occurrence in the vesicles of eruptive rocks as a secondary product, amygdaloids of chalcedony being very common in basalts, etc. In such rocks it is also found to form pseudomorphs after various minerals. In the acid or highly-silicated eruptive rocks, it appears to be, frequently, a normal constituent of their microfelsitic ground-mass, or base. It also very commonly forms more or less spherical concretionary masses, which usually possess a radiate structure. Sections passing through the centres of these spherulitic bodies, if examined in parallel polarized light, show a dark cross, and, when a quartz-wedge is used, negative double refraction; a fall in colour being observed in those quadrants through which the principal axis of the wedge passes.* Rosenbusch appears to regard chalcedony, not as a mixture, but as, possibly, a distinct species, of which the uniaxial character is doubtful.

Nepheline,—$3Na_2O, K_2O, 4Al_2O_3, 9SiO_2$,—occurs in clear colourless crystals which are generally combinations of the

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* For an exception to this rule see Teall's "British Petrography," p. 310.

hexagonal prism ∞P or $(10\bar{1}0)$ and basal pinacoids oP or (0001), occasionally modified by faces of the hexagonal pyramid. In this species is also included the dark greenish, grey or brown, greasy-lustred variety known as Elæolite.

Nepheline occurs in volcanic, elæolite, in plutonic rocks. The latter seldom exhibits any definite crystalline forms. The cleavage-planes, which are parallel to the prism and to the basal planes, are more often to be seen in sections of elæolite than in those of nepheline; and they become more marked in proportion to the decomposition which the crystals have undergone. The refractive index both in nepheline and elæolite is nearly that of Canada balsam; and sections of these minerals, consequently, show little or no irregularity of surface. The colours which they exhibit in polarized light are also low. Sections normal to the optic axis remain dark, in parallel polarized light, during complete rotation between crossed Nicols. In convergent polarized light, only a dark cross is to be seen in thin basal sections; in thick ones the usual uniaxial interference-figure is visible, but it generally appears more or less deformed. The double refraction is negative.

Inclusions of augite and hornblende microliths, fluid lacunæ, etc., are common in nepheline and elæolite, and are generally arranged in zones, which are parallel to the faces of the crystals.

Nepheline and elæolite are easily decomposed, and consequently they are often only represented by pseudomorphs. These are generally zeolites, sometimes analcime, but especially natrolite, which latter forms pale yellowish fibrous fringes along the margins and cleavage-planes of the crystal-section, the decomposition spreading further and further until none of the mineral is left unaltered.

Nepheline occurs in the rocks known as nephelinites and nepheline-basalts, phonolites, leucite-basalts, tephrites teschenites, etc.

Cancrinite contains, in addition to the nepheline molecule, $2CaCo_3+3H_2O$. When sections containing cancrinite are heated, Cohen has found that the mineral becomes turbid and more or less opaque; and this serves as one means of distinguishing cancrinite from nepheline. When heated in acids, cancrinite also effervesces briskly. In its unaltered condition thin sections are colourless and transparent.

Cancrinite occurs in the elæolite syenites, either in hexagonal prisms or in irregularly-shaped grains of a citron-yellow, greenish, or bluish-grey colour, or occasionally of a rose-red tint, due to finely-disseminated scales of specular iron.

Tourmaline.—$3R_2\ O_3\ SiO_2+3RO\ SiO_2$. The composition varies considerably, but $Al_2\ O_3$ and BO_3 are always present. The varieties of this mineral also differ greatly in colour, rubellite being red or pink, indicolite indigo-blue, while others are green or brown and the common variety, schorl, is black.

The crystals are rhombohedral and also hemimorphic; ∞ R, $(10\bar{1}0)$ and R, π $(10\bar{1}1)$ being common forms. Basal sections are usually hexagonal or trigonal; and these not unfrequently exhibit a zoned structure parallel to the faces of the prism. The crystals are often traversed by cracks. By transmitted light they appear of various colours, green, brown, yellow, etc.; and a deep blue or violet tint is often to be seen. The double-refraction of tourmaline is strong and negative and the pleochroism is very marked, especially in the strongly-coloured varieties. The ordinary ray invariably showing the greatest absorption. It is only in the micas and amphiboles, as pointed out by Rosenbusch, that we meet, among rock-forming minerals, with similarly strong absorption differences. Tourmaline, particularly the variety schorl, occurs more or less plentifully in many eruptive rocks, notably in Crystalline Schists, Syenites, and Granites, the latter often becoming peculiarly rich in schorl near their contact with other rocks.

In such cases the schorl frequently appears to have segregated in small nests and irregular aggregates of crystals.

Chlorite Group. In this group are included Ripidolite, Clinoclore and Pennine. Minerals which are, probably, all monoclinic in crystallization, although ripidolite and pennine are still doubtfully retained in the hexagonal system.

The crystals in their general aspect resemble hexagonal forms, and frequently give trigonal or irregularly polygonal sections transverse to the prism faces, such irregularities being due to the development of uneven numbers of faces of prisms of different orders.

The basal planes are always largely developed; and the perfect cleavage which occurs parallel to those faces, imparts a micaceous or scaly structure to these minerals.

Although well-formed crystals can hardly be considered rare, the chlorites are chiefly met with in irregularly-bounded scales or plates, often of very small dimensions. The irregularity of their boundaries may perhaps be attributed to the fact that the crystals very commonly exhibit more or less irregular flexure—this being usually well shown in sections taken at right angles or obliquely to the base. It is therefore evident that basal sections of such thin, bent, platy crystals would necessarily present irregular boundaries. In sections normal or oblique to the base, the ends of the sections often appear to be frayed out, owing to separation of the laminæ in the marginal portions of the crystals.

Chlorite also shows a fibrous structure at times; and the platy crystals or scales frequently occur in little, divergent, fan-like groups.

This divergent grouping may generally be well seen in small fissures or veins along which chlorite has been formed.

Chlorite also occurs in a finely pulverulent condition, in which neither structure nor definite form can be detected, even under very high magnifying powers, and it is then frequently distributed as a pigment in other minerals. In basal sections or cleavage plates of mica other cleavage planes, intersecting at about 60°, may often be seen under the microscope; but Rosenbusch states that, in chlorite, no such lines are ever visible.

In thin sections and cleavage plates the minerals of the chlorite group nearly always appear green by transmitted light, the colour ranging from pale to deep shades of green. The double refraction is very feeble, and its sign varies even in the same mineral.

Basal sections, or cleavage-plates and scales, when examined in parallel polarized light, appear either perfectly isotropic or sometimes, probably owing to flexure, they exhibit feeble double refraction. In convergent light, moderately thick cleavage plates of clinochlore show a good biaxial interference-figure with, sometimes, a wide separation of the polar rings. In thin plates only a dark cross is visible, which, on rotation of the plate, breaks up into hyperbolæ. The optic-axial angle in this mineral is variable; and the double refraction is sometimes positive, at others negative.

In thin plates of ripidolite and pennine only the dark cross is visible in convergent light. The intersection of the arms does not always lie in the centre of the field, and, on rotation, a separation of the arms into hyperbolæ is seldom clearly discernible.

The members of the chlorite group exhibit strong pleochroism when viewed in directions normal to the vertical axis. This is very marked in pennine. In a rather thick section of this mineral from Zermatt *o* = greenish-blue and *e* = orange-yellow. A cleavage-plate of the same mineral gives two similarly coloured dichroscopic images, viz.—greenish-blue, as in uniaxial crystals; but the cross of the interference-figure, visible in the same plate in convergent light, separates on rotation into hyperbolæ, as in biaxial crystals.

The chlorites vary considerably in chemical composition, but may be regarded as isomorphous mixtures of $3(Mg,Fe)O, 2SiO_2 + 2H_2O$ and $2(Mg,Fe)O, (Al_2,Fe_2)O_3, SiO_2 + 2 H_2O$ in the proportions of 3 : 2 to 1 : 2.

Heated on platinum foil, the chlorites part with water and become opaque, frequently changing their colour to reddish brown or black.

These minerals decompose in acids. They are never normal constituents of rocks, but are essentially products of alteration.

Chlorite may be said to constitute one of the most common diseases in rocks, its presence often marking the incipient decomposition of crystals along their cleavage-planes, while, at other times, it forms pseudomorphs and also frequently fills small cracks and veins.

TETRAGONAL SYSTEM.

What has already been said concerning the optical characters of hexagonal crystals (pp. 49, 51, and 120) applies equally to the crystals of the tetragonal system.

Rutile.—TiO_2. The common forms are combinations of the prism of the first order, ∞P (110), the prism of the second order, $\infty P \infty$ (100), the pyramid of the first order, P (111) and that of the second order, $P \infty$ (101). The crystals are usually twinned upon the last-mentioned face, or upon the pyramid face, $3 P \infty$ (301), a repetition of the twinning upon (101) giving rise to geniculate crystals, Fig. 76, while those twinned

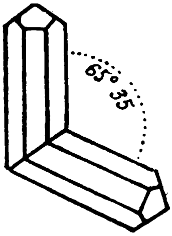

Fig. 76.

on the plane (301) show kite-shaped sections, Fig. 77. The crystals of rutile met with in rocks are usually of exceedingly small dimensions and are very perfectly formed. Larger crystals are, however, of frequent occurrence, and these commonly show a twin lamellation parallel to faces of P ∞ (101), the relation of the lamellæ to these faces being clearly seen in sections parallel to faces of the prism of the second order. In basal sections these lamellæ appear to intersect at right angles. The smaller twinned, knee-shaped crystals of rutile are often so arranged that they form reticulate groups, the mineral in this condition being known as sagenite (from σαγήνη, a net). This grouping of rutile crystals may sometimes be found forming intergrowths with specular iron, as in specimens from St. Gothard, the arrangement being clearly perceptible without the use of a lens. The double refraction of rutile is positive and very strong, and the surfaces of sections consequently show their irregularities very strongly under the microscope. Minute crystals enclosed in rock-sections depolarize in brilliant colours; but when of moderate thickness it is impossible to recognise interference phenomena. Rosenbusch states that the pleochroism is only to be made out in sections of medium thickness, the absorption for the extraordinary being greater than that for the ordinary ray.

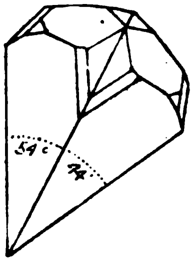

Fig. 77.

In convergent light, owing to twinning, the interference-figures generally appear irregular, often resembling those of biaxial crystals. The cleavage of rutile is well-marked and parallel to ∞ P (110). The high specific gravity of rutile renders it easily separable in Klein's or Sonstadt's solutions from most of the other rock constituents.

In syenites, amphibolites, gneiss, and various crystalline schists rutile is of frequent occurrence. The minute needle-like crystals so commonly seen under high powers, in sections of ordinary slates, after being referred to augite, hornblende, staurolite, etc., were finally found to be crystals of rutile.

Anatase.—$Ti\ O_2$. Common form, P or (111), generally occurs as an alteration-product.

It differs from rutile in having a lower specific gravity, 3·9; while that of rutile ranges from 4·20 to 4·27. The habit of anatase is also essentially pyramidal, and never prismatic as in rutile. The pyramid (111) in anatase usually occurs in combination with basal planes (001) and occasionally with faces of other pyramids. The crystals are almost invariably striated parallel to the basal edge. The cleavages are pyramidal and basal.

The refractive index of anatase, $o = 2{\cdot}554$, $e = 2{\cdot}493$, is nearly as high as that of rutile. The double refraction is negative. Basal sections, when examined in convergent polarized light, show a system of concentric rings traversed by a cross, the latter, however, often separating into hyperbolæ. The dichroism is not particularly strong.

By transmitted light the crystals usually appear colourless, yellow, brown, or bluish, and sometimes show zones of different colours in the same crystal.

Anatase is met with in granites, diorites, and other eruptive rocks, also in gneiss and in many sedimentary rocks of various geological ages.

A good rock for the study of this mineral is the well-known

Cleveland Iron Ore * A fragment the size of a hazel-nut, digested first in hydrochloric acid and then the residue in hydro-fluoric acid, will yield an abundant supply of crystals of anatase, mixed with a few zircons, tourmalines, and other minerals.

Tinstone.—SnO_2. Crystals are commonly combinations of the forms P (111), P ∞ (101), ∞ P (110), and ∞ P ∞ (100).

Twinning is frequent on faces of (101) giving rise to geniculate crystals, similar to those of rutile. The cleavage of tinstone is parallel to ∞ P ∞ (100), and is, as a rule, invisible in microscopic crystals. This, as pointed out by Rosenbuch, helps to distinguish sections of tinstone from those of rutile.

The double refraction of tinstone is positive and strong. By transmitted light sections show various shades of yellow, brown, or reddish-brown. By reflected light they exhibit a strong metallic or almost adamantine lustre.

The interference-figures seen in convergent light are seldom satisfactory, and frequently resemble those of biaxial crystals.

Tinstone occurs chiefly in gneiss and granite, especially near the contacts of granite with slates. It is also a frequent accessory in the rock termed greisen. †

Zircon.—ZrO_2 SiO_2. The crystals are commonly combinations of the prism of the 1st order, ∞ P (110), that of the 2nd order, ∞ P ∞ (100), the pyramid of the 1st order P (111) and other steeper pyramids, especially 3 P 3 (311). The prism faces are nearly always developed.

The cleavage parallel to ∞ P (110) is generally distinctly

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* "Memoirs of the Geological Survey," "The Iron Ores of Great Britain," Part I., 1856, p. 95, where an analysis of Cleveland Ore by Mr. A. Dick will be found, with an account of the anatase, which amounted to about 0·03 per cent. of the sample analysed.

† For further details concerning the mode of occurrence and the microscopic characters of tin-bearing rocks, the student may consult "Cornish Tinstones and Tin Capels," by J. H. Collins: a series of papers originally published in the *Mineralogical Magazine.*

seen in basal sections of the larger crystals; that parallel to the prism of the 2nd order is seldom visible under the microscope, except in traces; but in the smaller individuals it is rare to see even traces of cleavage-planes.

The double refraction is positive and strong, and the boundaries of the crystals appear sharply defined by broad, dark borders, due to total reflection. The microscopic crystals appear, as a rule, colourless, or of pale yellow, red, brownish, and clear violet tints; and the pleochroism discernible in the larger crystals is in these smaller individuals either barely or not at all perceptible.

A concentric, zoned structure is very common in crystals of zircon; and fluid, gas, and glass inclosures are also frequently seen in them.

The best confirmatory test for zircon consists, according to Rosenbusch, in fusing a small sample with bicarbonate of soda in a platinum capsule, 2 to 10 parts by weight of the bicarbonate being mixed with one of the zircon. If the smaller proportion of flux be employed, minute hexagonal, transparent, micaceous-like plates of ZrO_2, which are uniaxial and negative, may be washed out after fusion, by means of hot water slightly acidulated with HCl. When the proportion of zircon to flux is 1 to 10, after about five minutes' fusion at a red heat, the crystals of ZrO_2 washed from the fused mass exhibit quadratic forms, with strong double refraction.

Zircon occurs in crystalline schists, granites, syenites, gabbros, diorites, etc. Zircon crystals are also met with as inclusions in the crystals which help to constitute these rocks; and in such cases the enveloping mineral sometimes shows a distinctly pleochroic border around the included zircon.

Microscopic crystals of zircon occur plentifully in the Lower Bagshot sands of Hampstead, as first pointed out by Mr. Allan Dick.*

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* "On Zircons and other Minerals contained in Sand," "Nature," May, 1887, p. 91.

Scapolite essentially consists of silicates of alumina, lime, and soda, often with some NaCl; but it is of very variable composition. As a rock constituent, it generally appears in irregularly-shaped grains, and seldom exhibits any definite crystalline forms. It is a mineral which has a restricted occurrence in eruptive rocks, but is plentiful in certain Scandinavian gabbros. It is chiefly met with in gneisses and other crystalline schists, and in the limestones associated with them. In the latter the mineral is usually well crystallized, the crystals being combinations of the prisms of the 1st and 2nd orders with pyramidal terminations; but these last faces are not generally well developed. The cleavage parallel to $\infty P \infty$ (100) is, as a rule, well-defined, particularly in slightly altered crystals.

The double-refraction is negative and strong.

Thin sections of scapolite appear colourless, grey, or brownish by ordinary transmitted light. In polarized light they exhibit extremely brilliant colours, which, in very thin sections, are seldom lower than the orange or yellow of the 1st order. The refractive index is, however, low, and consequently irregularities on the surfaces of sections, when mounted in balsam, are barely perceptible.

In convergent light, basal sections show a sharply-defined uniaxial cross, which serves to distinguish the mineral from felspars and dichroite.

Meionite, which is closely related to scapolite, occurs plentifully in the limestone blocks of Somma, Vesuvius.

Idocrase is a lime-alumina silicate of variable composition, and containing a small percentage of combined water and usually some iron, mostly as sesquioxide. The crystals are generally combinations of the prisms of the 1st and 2nd orders terminated by faces of the protopyramid and basal planes, the latter dominating. Inclusions are seldom met with in them. The cleavage is ill-defined. Thin sections appear colourless, yellowish, greenish, or rose-red by transmitted light. More rarely they are reddish-brown or blue. The refractive index is high, and the surfaces of sections show any irregularities in strong relief. The double refraction is feeble, and the colours seen in polarized light are also low. In perfectly colourless crystals it is not uncommon to find that in parallel polarized light they exhibit distinctly-coloured concentric zones, which in some cases are found to vary in their optical sign, some being positive and others negative. The double refraction of Idocrase is, however, properly, negative. In convergent light thick basal sections often show a peculiar interference-figure, the cross separating into hyperbolæ as in biaxial crystals. In thin sections, however, only a feeble dark cross is visible. The pleochroism is weak.

Altered conditions of Idocrase have not yet been observed. It .occurs chiefly in metamorphic rocks, especially in limestones.

Melilite,—$12CaO, 2Al_2O_3, 9SiO_2$—often with alkalies (3 or 4 per cent.) or magnesia partly replacing the lime, and some sesquioxide of iron replacing part of the alumina. The basal planes are generally the most strongly-developed faces in crystals of melilite—faces of the prism being, as a rule, poorly represented or absent, in which case the mineral assumes the form of irregularly-bounded tables. In the short-prismatic crystals sections taken parallel to the principal axis are lath-shaped, while basal sections are square, octagonal, or circular. At times the mineral occurs in irregularly-shaped grains. Twins are not of frequent occurrence.

By transmitted light melilite appears colourless, yellowish, or brownish. The more ferriferous kinds, as those in the lava of Capo di Bove, exhibiting the latter tint. The refractive index is high, and the double-refraction negative and very weak. In polarized light the interference-colours are consequently low down in the first order.

Owing to the colourless, or feebly-coloured character of the crystals, pleochroism is not, as a rule, discernible.

A curious structure is seen in crystals of melilite, which is believed to be due to the presence of vitreous matter in inclusions of peculiar form and arrangement. In sections parallel to the principal axis striæ are seen which resemble cleavage-cracks, and which run, sometimes singly, sometimes in bundles, parallel to the principal axis. Inclusions also extend from the basal planes, often enlarging as they pass inwards into peg-like, bulbous, or funnel-shaped forms. From these, lateral processes are sometimes seen to extend in directions parallel to the basal planes. The pegs do not pass quite halfway across the crystal, so that a band of unstriated or unpegged crystal is seen to extend across the middle of a section in a plane parallel to the basal pinacoids. This has been termed peg-structure by Stelzner.

Melilite becomes altered into what is believed to be a zeolitic mineral, which is developed in the direction of the striated or peg-like structure (*i.e.*, normal to the basal planes), in fine, fibrous growths showing strong double refraction, the fibres occasionally forming divergent groups. An alteration of melilite into garnet has also been observed. The mineral is a constituent of certain basalts, and especially of lavas containing leucite and nepheline.

RHOMBIC SYSTEM.

In this system, as already mentioned, there are three optical elasticities to be recognised; viz., greatest, mean, and least; and the three axes of elasticity lie at right angles to one another, and respectively coincide with, or are parallel to, the three crystallographic axes. One of these axes is the common acute bisectrix for light of all colours, another the obtuse bisectrix, and the optic axes for light of different colours are symmetrically dispersed with reference to these bisectrices, and also lie in the same plane with them. If the acute bisectrix be the axis of least elasticity, the crystal is positive; but if it be that of greatest elasticity, it is negative. The axis of mean optical elasticity is never a bisectrix. It always lies at right angles to the plane in which the optic axes and their bisectrices are situated, and it is consequently termed the optical normal.

In sections of rhombic crystals the method of ascertaining which of the directions of extinction is the axis of greater (not necessarily of greatest) optical elasticity has already been described (pp. 90 *et seq.*). If both be bisectrices, the section will show no interference-figure in convergent light; under such circumstances we know the third axis to be that of mean elasticity. On the other hand, if the section show an interference-figure, we know that it is cut at right angles, or approximately at right angles, to one or other of the bisectrices; consequently we have to determine which of the two directions of extinction is the optic normal, and this will, of course, be the one which lies at right angles to the optic-axial plane, and corresponds with the *broad* dark bar of the interference-figure when the section is in the normal position. If this bar correspond with the direction of the lesser elasticity, it is evident that the narrow bar of the cross corresponds with the axis of greatest elasticity; but if the direction of the broad bar be the direction of greater, then that of the narrow bar will represent that of least elasticity. Since these three axes of optical elasticity correspond in direction with the three crystallographic axes, it is also evident that they will be respectively parallel to those edges of the crystal which result from the contact of the macro-, brachy-, and basal pinacoids, or to any cleavage-planes which happen to be parallel to those pinacoids, or parallel to the edges formed by them. The interference-figures of rhombic crystals are symmetrical to two lines which respectively correspond with the two bars forming the cross in the normal position of the section.

For notes on rhombic dispersion, see pp. 72 *et seq.*

Rhombic Pyroxene Group.

Hypersthene, Enstatite, and Bronzite.

In this group are included the minerals hypersthene, enstatite, and bronzite.

They have the general formula $RSiO_3$, in which $R = Mg$ or Fe, or both; isomorphous substitution of the latter for the former element occurring in various proportions, and giving rise to ferriferous varieties, as in the variety of enstatite known as amblystegite.

The crystals of the rhombic pyroxenes usually have a short-prismatic habit. Their cleavages are parallel to faces of the rhombic prism of the 1st order, $\infty P\ (110)$, and intersect at about 92°. These are not, however, very distinct cleavages, as a rule; but in the rhombic pyroxenes occurring in the older crystalline rocks, they are very commonly traversed by a much more distinct cleavage parallel to the brachypinacoid, $\infty \breve{P} \infty\ (010)$. Occasionally very imperfect cleavages parallel to the macropinacoid are also to be detected. In sections parallel to the vertical axis all of these cleavage planes lie parallel to that axis. The crystals are also frequently traversed by irregular cracks (not cleavages) in directions transverse to the vertical axis.

Sections of these minerals are more or less translucent, and by transmitted light are seen to vary in colour from brown, reddish, or greenish in hypersthene, to yellowish or greyish tints in enstatite, which latter is often approximately colourless. The refractive index is high, especially in the ferriferous varieties. The double refraction in enstatite and bronzite is positive, in hypersthene it is negative, but in all cases it is weak, and the colours in polarized light are consequently low, those of hypersthene in moderately thick sections being seldom higher than red of the 1st order, while those of enstatite and bronzite do not rise above the yellow. The vertical axis is that of least, and the brachydiagonal that of greatest elasticity, consequently in these crystals $a = \mathfrak{a}$, $b = \mathfrak{b}$, $c = \mathfrak{c}$, and the optic-axial plane is therefore always parallel to the brachypinacoid, or to the corresponding and most strongly-marked cleavage.

The ferriferous varieties have a wider optic-axial angle than those poorer in iron. Owing to the wide separation of the axes, the angle must be measured in oil.

In sections normal to the axis of greatest elasticity, the dispersion is $\rho > v$ for the more ferriferous varieties, and $\rho < v$ for those poor in iron.

The pleochroism, also, which in enstatite and the less ferriferous bronzites is scarcely perceptible, becomes more marked in proportion to the increase in the percentage of iron. Sections of amblystegite are strongly pleochroic, as are also moderately thick sections of hypersthene when the mineral has not become bleached by the separation of iron, one of the changes ("Schillerization" of Judd), common in the hypersthene of certain plutonic rocks. The pleochroism of hypersthene is a = reddish-brown, b = reddish-yellow, c = green.

Owing to the fact that the optic-axial plane in hypersthene and enstatite is parallel to the direction of most perfect cleavage ($\infty \breve{P} \infty$), it follows that such cleavage plates show no definite interference-figure in convergent polarized light. These minerals are met with in such rocks as norite, gabbro, peridotite, andesite, trachyte, etc. They also occur at times in serpentines which have resulted from the alteration of rocks mainly composed of minerals rich in magnesia, especially olivine.

In Figs. 78 and 79 the mutual relations of the crystallographic axes, the optic axes, the axes of elasticity, and the cleavages to one another and to the pinacoidal faces in enstatite and hypersthene are diagrammatically indicated in plane projection, Fig. 78 representing enstatite, and Fig. 79, hypersthene.

In these figures $a=\mathfrak{a}$ $b=\mathfrak{b}$ and $c=\mathfrak{c}$; but to avoid confusion, only the symbols of the crystallographic axes have been employed, those of the corresponding axes of optical elasticity being omitted.

Figs. 78, I. and 79, I. show the basal planes in enstatite and hypersthene respectively. Figs. 78, II. and 79, II. severally represent the macropinacoidal sections of these minerals, while their brachypinacoidal sections are given in Figs. 78, III. and 79, III.

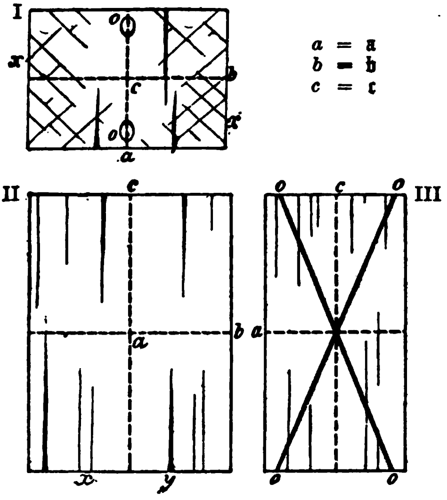

Fig. 78.

In all of these drawings, c denotes the vertical crystallographic axis and also the axis of least elasticity, $\mathfrak{c}$; $b=$the macrodiagonal and also the axis of mean elasticity, $\mathfrak{b}$; $a=$the brachydiagonal and also the axis of greatest elasticity, $\mathfrak{a}$. o $o=$the optic axes.

In enstatite the polar rings are indicated on the basal section by *o o*, Fig. 78, I.; $\mathfrak{c}$ in this figure being the acute, and $\mathfrak{a}$ the obtuse bisectrix. The crystal is consequently optically positive.

In hypersthene the poles of the optic axes *o o* are indicated on the macropinacoidal section, Fig. 79, II. Here the axis of greatest elasticity, $\mathfrak{a}$, is the acute, and $\mathfrak{c}$ the obtuse bisectrix, as indicated diagrammatically in the brachypinacoidal section, Fig. 79, III.

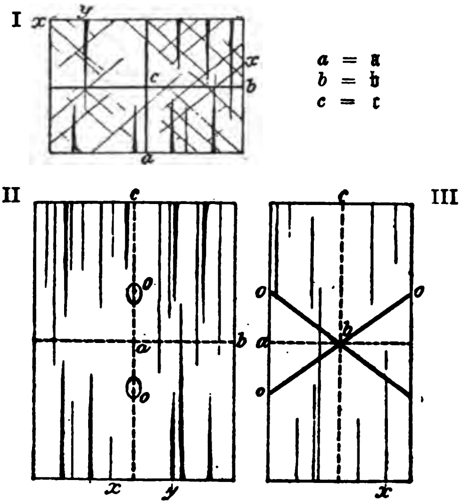

Fig. 79.

In all the drawings the fine lines, *x x*, denote the traces of the cleavage planes parallel to faces of the prism ∞ P (110), while the thick lines, *y*, indicate the direction of the brachydiagonal cleavage, which in Figs. 78. III. and 79. III. is assumed to be parallel to the paper, and, of course, is not visible. This cleavage is very strongly marked in hypersthene, but in enstatite and bronzite it is much less so.

Bastite, or Schillerspar, has approximately the same composition as serpentine, when pure, viz: $H_2\,Mg_3\,Si_2\,O_8 + aq$. Some of the magnesia, however, is usually replaced by protoxide of iron. It is essentially an altered condition of enstatite or bronzite in which the percentage of iron is small. Hence it must be regarded as a pseudomorph. The form is that of enstatite and bronzite, but it also frequently occurs in irregular plates with a more or less fibrous structure. The cleavages characteristic of enstatite and bronzite are also present in bastite, that parallel to the brachypinacoid being even more strongly marked than in the unaltered minerals; and the cleavage surfaces display a silky or more commonly a metallic lustre.

Thin cleavage flakes and sections appear of a pale-yellowish or greenish colour by transmitted light, and show a fibrous structure, frequently accentuated by the segregation of minute granular bodies, many of which are often opaque and black, and are probably due to the separation of iron from the original mineral and the development of magnetite.

The directions of extinction in the cleavage-plates of bastite are parallel and at right angles to the fibrous structure, and to the lines of opaque inclusions associated with them. If such a cleavage-plate be so arranged in parallel polarized light that the fibres and lines of inclusions lie at 45° to the principal sections of the crossed Nicols, it will be seen, on inserting a quartz-wedge in the same direction, that a rise in colour ensues; [*i.e.*, if the plate of bastite only partially underlies the wedge], the red of the 1st order in the latter being seen, where it overlies the bastite, to be faulted into the region of the yellow of the same order. If we examine the same cleavage-plate in convergent light, we shall see an interference-figure, since the optic-axial plane in bastite is *parallel to the macropinacoids and* $\mathfrak{a}$ *is the acute bisectrix;* or rather, we shall see the dark-crossed bars of the interference-figure, which, on rotation, break up into hyperbolæ, and we can thus ascertain that the optic-axial plane is parallel to the fibres and lines of inclusions already observed. The rise in colour, previously indicated by the insertion of the quartz-wedge in the direction of the fibres, shows that the axis of elasticity parallel to them is an axis of less elasticity than that of the optic normal, or direction of extinction normal to the optic-axial plane. It is therefore the axis of least elasticity $\mathfrak{c}$; but in this case it is also the obtuse bisectrix. The acute bisectrix $\mathfrak{a}$ is consequently normal to the planes of cleavage. The angle of the optic axes in bastite varies from 20° to nearly 90° and the dispersion is $\rho > v$.

The pleochroism is too feeble to be detected in any but thick plates.

The relation of the axes of elasticity, the optic axes, and the brachydiagonal cleavage are diagrammatically shown in Fig. 80, the numbers I., II., and III., as well as the reference

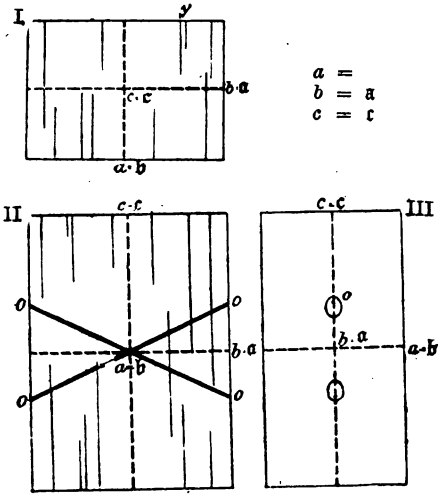

Fig. 80.

letters, having the same signification as in Figs. 78 and 79.

In Fig. 80, I., II., and III., however,

$$a=\mathfrak{b},\ b=\mathfrak{a},\ c=\mathfrak{c}$$

On comparing Figs. 78, 79, and 80, the student will easily see that, owing to the relative positions of the optic-axial plane to the strong brachydiagonal cleavage, no indications of an interference-figure are seen, in convergent light, in cleavage-plates of enstatite and bronzite, while cleavage-plates of bastite show the dark cross in the normal, or the hyperbolæ in the diagonal position, or, as it is laxly expressed, they "show a bisectrix." When we consider, however, that bastite is merely an altered condition of enstatite or bronzite, we naturally feel anxious to know why this change has taken place in the position of the optic-axial plane.

The question does not, as yet, appear to have met with any definite solution; but since, by heating sections of selenite and some other minerals in convergent polarized light, we can actually see such a change in the position of the optic-axial plane take place; and since, in some of these cases, if the temperature be sufficiently raised, the change becomes permanent, it seems quite possible that the rhombic-pyroxene-bearing rocks may have experienced considerable variations of temperature, and that these changes, in conjunction with other causes, may not merely have partially undermined the chemical constitutions of members of the rhombic pyroxene family, but may also have seriously affected them with regard to the transmission of light. Whether under such circumstances the development of heat was due to pressure, and how far pressure or heat may have been individually or conjointly concerned in effecting the change in the position of the optic-axial plane in bastite, has yet to be explained.

From its pseudomorphic nature, bastite is only met with in rocks which contain, or which have originally contained, enstatite or bronzite, or possibly other pyroxene. Bastite is of common occurrence in olivine-bearing rocks, and especially in serpentines.

Rhombic Amphibole Group.

Of this group there are two members:—

Anthophyllite,—(Mg, Fe) SiO_3,—and **Gedrite,**—Mg, $Al_2 SiO_6$. Both of these minerals occur in gneissic rocks and hornblendic schists. The crystals are prismatic in habit, the observed faces being ∞ P, (110), and $\infty \bar{P} \infty$, (100). The angle of the prism (110) is approximately that of hornblende, 124° to 125°. The crystals never show any terminations, and have a tendency to form striated aggregates and divergent and platy groups.

There is a very perfect cleavage parallel to the macropinacoid, $\infty \bar{P} \infty$ (100), as indicated by the thicker strokes, *z*, in Fig. 81, while the finer strokes, *x*, denote a distinct cleavage parallel to the faces of the prism, ∞ P (110).

A somewhat imperfect cleavage parallel to the brachypinacoid, $\infty \breve{P} \infty$ (010), may likewise be detected, as a rule; but this is not represented in Fig. 81. The crystals also frequently show a tendency to split in directions rudely parallel to the basal planes 0 P (001).

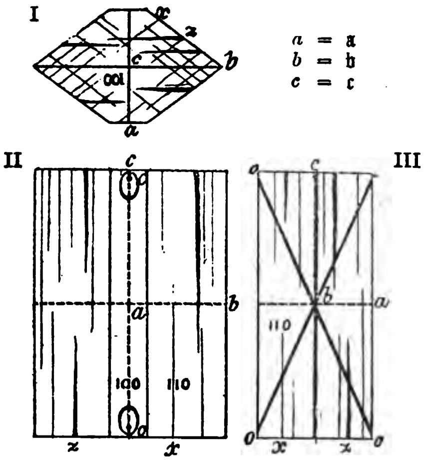

Fig. 81.

By transmitted light, the minerals of this group appear colourless, yellowish, or yellowish-green, and sometimes of a reddish-brown colour. The double refraction may be either positive or negative, the former usually in anthophyllite, and the latter in gedrite; and, as it is very strong, the colours seen in polarized light are also strong, a circumstance which serves to distinguish sections of these minerals cut parallel to the vertical axis from the rhombic pyroxenes, especially from those poor in iron. The directions of maximum extinction are, as in all other rhombic crystals, parallel and at right angles to the crystallographic axes, or to the edges formed by the pinacoidal faces.

The optic-axial plane lies in the brachydiagonal section; consequently cleavage plates parallel to the macropinacoids always give an interference-figure in convergent light; but, owing to the very variable angle of the optic axes, it is necessary, in many cases, to make the observation in oil, the apparent angle in oil, for anthophyllite being sometimes as much as 82°, but diminishing in some examples of gedrite to 47°. The dispersion varies. The pleochroism also varies, being stronger in the deeper-coloured specimens. For vibrations parallel to $\mathfrak{c}$ the colours may range from greenish to yellowish-brown, or even colourless, while vibrations parallel to $\mathfrak{a}$ or $\mathfrak{b}$ give a pinkish-brown. The absorption is $\mathfrak{c}<\mathfrak{a}=\mathfrak{b}$.

Inclusions of magnesian mica, magnetite, and specular iron are common in the rhombic amphiboles. Lamellar intergrowths of rhombic and monoclinic amphibole are not uncommon. The former may be recognised, when cleavage-plates parallel to the macropinacoid are examined in convergent light, by a bisectrix lying at right angles to the planes of cleavage, while the monoclinic lamellæ give an oblique view of the system of polar rings about one axis, as represented diagrammatically in Fig. 82, where the middle band marked M indicates monoclinic amphibole, and R, R lamellæ of rhombic amphibole. In each of these lamellæ the small circular disc is intended to represent the field of the polariscope or microscope. Within the upper and lower discs, the crosses (bisectrices) seen in convergent light are shown, while in the middle disc part of a system of axial rings is represented, traversed by a dark bar. The drawing shows the figures in the normal position, the directions of the Nicols being indicated by the dotted lines N N, N′ N′.

If the cleavage plate were turned through 45° into the diagonal position, the crosses in the upper and lower discs would separate into hyperbolæ, Fig. 82*a*, while the dark bar in the middle disc would become curved, and sweep diagonally across the field and out of view, leaving only the rings visible, Fig. 82*b*.

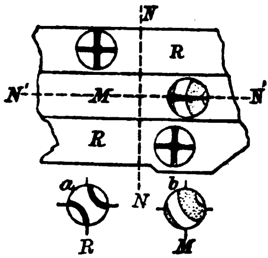

FIG. 82.

The rhombic amphiboles are chiefly met with in crystalline schists, especially in hornblende schists and slates, and in hornblendic gneiss. They also occur in serpentines which have resulted from the alteration of eruptive rocks rich in olivine.

Olivine.—(Mg, Fe) SiO_3. The proportion of iron to magnesium varies considerably, while in Fayalite the formula becomes $Fe_2 \, SiO_4$. The forms generally met with in combination are the prism ∞P, the macro- and brachy- pinacoids, constituting the rhombic prism of the second order, or right rectangular prism, $\infty \bar{P} \infty$ and $\infty \check{P} \infty$, together with faces of

$\infty\breve{P}2$ and the doma planes $\bar{P}\infty$, $\breve{P}\infty$ and $2P\infty$. Basal planes $0P$ are also frequently developed. The angles of the crystals are often rounded, and the faces are sometimes corroded by the action of the surrounding magma; the rounding process having often been carried so far that a rounded grain or pellet results, upon which no trace of a crystal-face can be detected. Granular crystalline aggregates of olivine are also common in certain rocks; and in the glassy basalt of the Sandwich Islands exceedingly beautiful crystallites of olivine occur, many of them similar in their skeleton-structure to some of the crystallites seen in blast-furnace slags. The forms of these olivine crystallites vary greatly, and transitions may be observed from those consisting merely of two minute curved rods, with their convex sides almost in contact, and from which fine pectinate outgrowths have taken place, Fig. 83, to forms which are completely filled in, and which closely or perfectly resemble some of the larger crystals. Cleavage planes parallel to the brachypinacoid $\infty\breve{P}\infty$ (010), and also to the basal plane $0P$ (001), are frequently to be seen in sections of olivine crystals, but they are imperfect. Traces of still less perfect cleavages parallel to the macropinacoid $\infty\bar{P}\infty$ (100), and to the prism ∞P (110) may also be occasionally detected. The crystals are likewise very generally traversed by irregular fissures, often strongly-defined. The highly ferriferous variety, fayalite, usually shows more perfect brachydiagonal cleavage than ordinary olivine.

×250

Fig. 83.

Thin sections of olivine appear transparent and colourless, or of a faint greenish tinge by transmitted light. The thin tabular crystals of fayalite found by Iddings in the obsidian of the Yellowstone National Park, have a light honey-yellow colour, while, occasionally, ferriferous varieties are red or reddish-brown. Owing to the high refractive index, the surfaces of sections of olivine always have a very rough aspect. The double refraction is exceedingly strong, and is positive; and the colours seen in polarized light are also strong, being usually of the 2nd or 3rd order.

The optic-axial plane lies parallel to the basal planes; and the acute bisectrix is the axis of least elasticity, $\mathfrak{c}$, which also coincides with, or is parallel to, the brachydiagonal *a*, and consequently $b = \mathfrak{a}$ and $c = \mathfrak{b}$, as shown in Fig. 84. Sections parallel to the macropinacoid will, in convergent light, give an interference-figure, as indicated by the polar rings of the axes *o o* in Fig. 84, II.

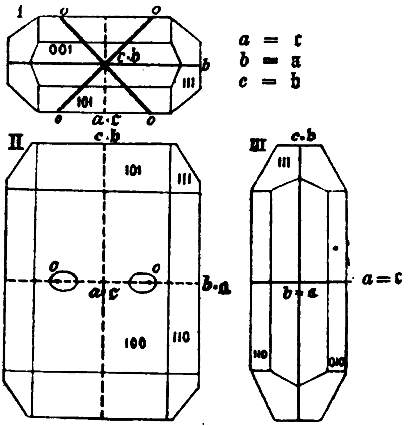

FIG. 84.

The optic-axial angle is a very wide one, 2 V, for sodium light being 87° 46′. The dispersion is weak, $\rho < v$. The pleochroism is feeble, even in fayalite, in which a pale greenish-yellow has been observed parallel to the macrodiagonal, and golden-yellow parallel to the vertical axis. If sections of olivine, not too poor in iron, be heated, they assume a red colour, and become more or less pleochroic.

One of the most common changes to which olivine is liable is its conversion into serpentine. The process begins at the surfaces of the crystals, as well as along the cleavage planes, and especially in the irregular fissures, which now become more pronounced. The incipient change is marked by the development of yellowish-green or pale green fibrous matter, the fibres being at right angles to the fissures and to the bounding surfaces of the crystals. While this is going on, a separation of iron takes place, which results in the formation of magnetite, hematite, or limonite. As the alteration progresses, the fringes of chrysotile or fibrous serpentine spread further into the crystal, which, in section, would now show irregular patches of unaltered olivine, separated from one another by serpentinous fringes, Fig. 85. Ultimately the last vestiges of olivine disappear, the alteration of the crystal is complete, and a pseudomorph of serpentine is the result. In this the original fissures and cleavage planes of the olivine can still be traced, so that the pseudomorph exhibits a mesh-like structure. With some practice this may often be detected in serpentines which have resulted from the alteration of rocks containing olivine. Replacement of olivine by other

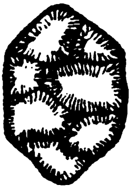

Fig. 85.

minerals is also frequent, pseudomorphs of calcite after this mineral being by no means uncommon.

In olivines rich in iron, the alteration which takes place also begins at the surfaces of the crystals and along the fissures by which they are traversed; but in such cases it does not result in the formation of serpentine, but of hematite, which frequently becomes converted into limonite.

Remarkable changes also occur in certain crystalline schists, gabbros, and other rocks, by which minerals of the amphibole group, actinolite, tremolite, and anthophyllite are formed about the surfaces of olivine crystals. Cases have also been met with in which olivine crystals have been converted into an aggregate of small amphibole crystals, mixed with serpentine or chlorite and magnetite.

Olivine occurs in peridotites, gabbros, basalts, etc.

Topaz.—$5\,Al_2\,Si\,O_5 + Al_2\,Si\,F_{10}$. The crystals are frequently combinations of the prisms ∞P (110), $\infty \breve{P} 2$ (120), the brachydomes $2\,\breve{P}\infty$ (021), and the pyramid P (111). The basal planes oP (001) sometimes enter into this combination, but in minute crystals they are as a rule very subordinately developed.

The cleavage *w* (Fig. 86), which is parallel to the base, is perfect and well-shown. Microscopic sections of topaz are transparent and always colourless. The double refraction is positive, and the colours seen in polarized light, although brilliant in thick cleavage-plates, are rather weak in thin sections, seldom exceeding yellow of the first order.

The optic-axial plane lies in the brachydiagonal section and the axis of least elasticity $\mathfrak{c}$; also the vertical crystallographic axis c is the acute bisectrix. The optic-axial angle is very variable and wide, 2 E, the apparent angle in air, ranging from 70° to 120°. Even in thick cleavage plates the pleochroism is weak; in thin sections it is imperceptible.

Basal cleavage-plates and sections show an interference-figure in which the dispersion is seen to be $\rho > v$; and the fact that a section showing an interference-figure does not exhibit any cleavage planes, since it is parallel to the cleavage, is an important means of distinguishing topaz. Inclusions of water, liquid carbon-dioxide, and saturated solutions of salts containing cubic and rhombohedral crystals, are common in topaz.

It is met with chiefly in granitic rocks, especially those in which tinstone occurs. In Fig. 86, III., portion of a crystal is shown, separated by the basal cleavage *w*.

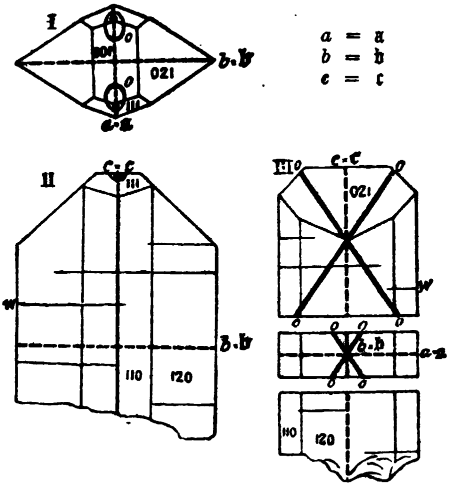

FIG. 86.

Dichroite (Iolite, Cordierite).—$Mg_2 (Al, Fe)_4 Si_5 O_{18}$. The percentage of ferric oxide and alumina vary, and ferrous oxide is possibly present at times. As a rock-constituent, dichroite occurs both in irregular grains and also in crystals, the latter being almost invariably combinations of the prism ∞P (110), the brachypinacoids $\infty \breve{P} \infty$ (010), and basal planes $0 P$ (001). Pinite and other minerals, pseudomorphous after dichroite, are also frequently bounded by the same forms. The crystals of dichroite are often twinned much in the same manner as aragonite. When cleavages can be detected, they are found to lie parallel to the brachypinacoid, *y*, Fig. 87, I. and II.

In sections, the mineral usually appears colourless; but in moderately thick plates yellowish and violet tints may also be seen. The index of refraction is low, and the double refraction is weak and negative.

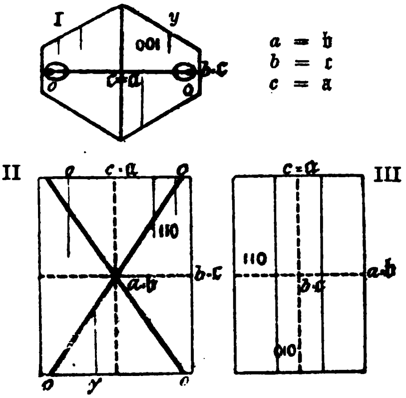

Fig. 87.

The optic-axial plane lies in the macrodiagonal section, and the axis of greatest elasticity is the acute bisectrix, and also coincides with, or is parallel to, the vertical crystallographic axis.

Hence $a=\mathfrak{b}$, $b=\mathfrak{c}$, $c=\mathfrak{a}$. The optic-axial angle is extremely variable, the apparent angle in air, 2 E, ranging from 64° to 150°. The dispersion, $\rho < v$, is feeble. In thick plates dichroite exhibits well-marked pleochroism, but in thin sections this is often imperceptible. Thin sections parallel to the vertical axis, however, frequently show it. The absorption is $b > a > c$.

In sections which are not parallel to (001) pleochroic, borders are visible around inclosures of various kinds, which give a brilliant yellow when the vibrations are parallel to the vertical axis. Basal sections do not show this phenomenon. The pleochroism of dichroite sometimes becomes more distinct when the mineral is heated; but this, in thin sections, occasionally gives an opposite result. Pinite, chlorphyllite, and several other minerals owe their origin to the alteration of dichroite. Some of these pseudomorphs must be regarded as variable mixtures of muscovite, talc, chlorite, and limonite. Dichroite occurs chiefly in granite, gneiss, and various crystalline schists.

Zoisite,—$H_2\ Ca_4\ Al_6\ Si_6\ O_{26}$,—occurs either in individual crystals or in divergent aggregates of prisms. The forms are usually ∞P (110), with an angle of 116° 26; $\infty \breve{P} \infty$ (010), and very commonly other prisms, as $\infty \breve{P} 2$ (120); $\infty \breve{P} 4$ (140), etc. Terminations are rare, and when present they consist generally of the faces of P (111), and $2 \breve{P} \infty$ (021). The cleavage *y* is perfect parallel to the brachypinacoid, and the parallel striæ to which it gives rise are very distinctly shown in basal sections and in those parallel to the prism faces (Figs. 88 and 89). A much less distinct cleavage also exists parallel to the macropinacoid. Sections likewise exhibit a

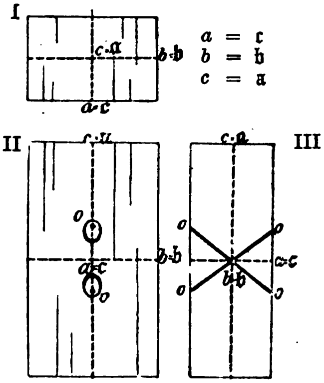

FIG. 88.

transverse fission parallel to the basal planes, which is somewhat irregular.

Under the microscope zoisite appears grey or greenish grey, or, when perfectly fresh, colourless. Some varieties (Thulite, etc.) are red or yellowish by transmitted light, but these contain manganese. Thulite displays strong pleochroism, while ordinary zoisite shows none. The colours in polarized light are feeble. The refractive index is high, and consequently irregularities upon the surfaces of sections appear strongly defined.

The optic-axial plane sometimes lies parallel to the brachypinacoid, as shown diagrammatically in Fig. 88, while at others it is parallel to the basal plane, as in Fig. 89. In either case the double refraction is positive, the axis of least elasticity, $\mathfrak{c}$, being the acute bisectrix; and in both cases $\mathfrak{c}$ is parallel to, or coincides with, the brachydiagonal *a*. In the first instance, in which the optic-axial plane is parallel to (010), $a=\mathfrak{c}$, $b=\mathfrak{b}$, $c=\mathfrak{a}$. In the second, where it is parallel to the base (001), $a=\mathfrak{c}$, $b=\mathfrak{a}$, $c=\mathfrak{b}$.

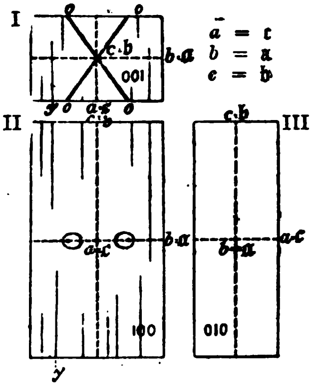

FIG. 89.

The optic-axial angle is extremely variable, ranging from almost 0° to 100° in air. Sections parallel to the macropinacoid (100) give an interference-figure in convergent light which exhibits very strong dispersion. This, in cases like that shown in Fig. 88, is always $\rho < v$, while in that represented in Fig. 89 it is $\rho > v$.

Zoisite sometimes displays peculiarities in twinning, of which the student will find a description in Rosenbusch's "Mikroskopische Physiographie" (2nd ed., vol. i., p. 421). Lamellar twinning is also to be seen in this mineral.

Zoisite occasionally results from the alteration of triclinic felspars, as in certain gabbros. It is met with chiefly, however, in amphibolites and various hornblendic schists, also in eclogite. Thulite sometimes occurs in the hornblende-porphyrite, known as *porfido-rosso-antico*.

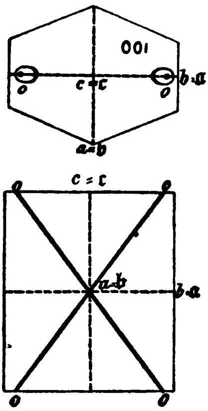

Fig. 90.

Staurolite, approximately $Fe\,O, 2\,Al_2\,O_3, 2\,Si\,O_2$, frequently with 2 or 3 per cent. of magnesia, replacing ferrous oxide. Sections of the larger crystals usually show a great number of included quartz granules, together with carbonaceous matter, kyanite, tourmaline, mica and rutile, these inclusions often constituting nearly one half the bulk of the crystal. The microscopic crystals, however, are, for the most part, much more free from impurities. The crystals are commonly combinations of the prism ∞P (100), with brachypinacoids $\infty \check{P} \infty$ (010), and basal planes $0 P$ (001). Macrodomes $\bar{P} \infty$ (101) are often present, but they are usually very small, and are by no means of constant occurrence. A platy structure parallel to the base is sometimes seen. The usual types of twinning are upon the planes $\frac{3}{2} \check{P} \infty$ (032), and $\frac{3}{2} \check{P} \frac{3}{2}$ (232), and are of frequent occurrence even in microscopic crystals. There are cleavages parallel to (010) and to (110), but, as a rule, they are very indistinct, and frequently no cleavage is perceptible.

The colour by transmitted light is reddish-brown, or yellowish-brown. Staurolite has a very high refractive index, and the surfaces of sections show their irregularities distinctly. The double refraction is positive and strong, and the colours seen in polarized light are vivid.

The optic-axial plane lies parallel to the macropinacoid $\infty \bar{P} \infty$ (100), and the vertical axis c, also axis of least elasticity $\mathfrak{c}$, is the acute bisectrix. The optical scheme is, therefore, $a = \mathfrak{b}$, $b = \mathfrak{a}$, $c = \mathfrak{c}$ (as shown in Fig. 90).

The dispersion is feeble and $\rho > v$. The pleochroism is distinctly perceptible, but is rather feeble. Staurolite occurs chiefly in the crystalline schists, especially in mica-schist and gneiss. The crystals are sometimes so imperfectly developed as to appear rounded.

Andalusite.—$Al_2 O_3 SiO_2$. The crystals are usually combinations of the prism ∞P (110), with basal planes $0 P$ (001), and occasionally doma planes. Twinning upon the plane (110) has been observed, but it is extremely rare. Of the cleavage, which is prismatic, little is to be seen in microscopic crystals. These are translucent, and appear colourless, or, more rarely, of a reddish tint in transmitted light.

The larger crystals, such as those from the Tyrol, are usually mixed to a considerable extent with mica, kyanite, etc. Some Brazilian specimens are, however, perfectly transparent, and show well-marked pleochroism. The refractive index is rather high. The double refraction is negative and weak, and the colours seen in polarized light are low in the first order, a circumstance which Rosenbusch points out as giving an important means of distinguishing andalusite from sillimannite. The optic-axial plane lies in the brachydiagonal section, and the axis of greatest elasticity $\mathfrak{a}$, which also coincides with, or is parallel to, the vertical crystallographic axis c, is the acute bisectrix; consequently $a = \mathfrak{c}$, and $b = \mathfrak{b}$, as shown in Fig. 91.

In Fig. 91, III., the optic axes are repeated, in order that their emergence on the basal plane may be shown, since it is the basal section which is normal to the acute bisectrix $\mathfrak{a}$, and, in this section, the interference-figure will be seen in convergent light. The optic axes may, of course, emerge also on the macropinacoidal section, to which the obtuse bisectrix $\mathfrak{c}$ is normal; but in this case the separation of the polar rings is greater by 5 degrees or more. The optic axial angle, $2V = 83°$ to $85°$.

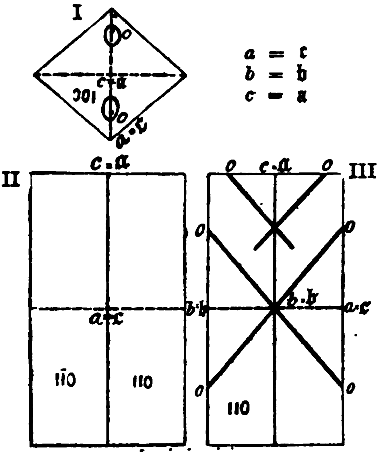

FIG. 91.

The pleochroism of andalusite is most variable, being sometimes very strong, at others inappreciable. In thin sections, for the axes a and b, it is greenish or colourless, for the vertical axis, rose-red.

Crystals of andalusite often contain carbonaceous matter and inclusions of other minerals, particularly mica, as well as fluid lacunæ.

Chiastolite is a variety of andalusite prevalent in slates where they come in contact with, or occur in the vicinity of granite. It is also met with in mica-chist, gneiss, and some of the less crystalline schists.

The peculiar markings to which the mineral owes its name, though originally regarded as slaty material, are now considered by Rosenbusch to be due to the inclusion and symmetrical arrangement of particles of carbonaceous matter. W. Müller, however, in a recent paper,* describes the inclusions as consisting of clay slate, and exhibiting the same lamination as the surrounding rock. These markings are well seen in sections of the larger crystals, especially in some of the American specimens, which frequently present no crystalline form, occurring as elongated fusiform bodies, somewhat resembling diminutive cigars, pointed at both ends. The very minute crystals also exhibit similar inclusions, when broken or cut transversely.

Fig. 92.

A good example from the slate occurring close to the Dartmoor granite near Okehampton, in Devon, is shown in Fig. 92 (magnified 250 linear). The small crystals usually

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* "Neues Yarbuch," 1888, vol. i., pt. 2, p. 175.

occur in forms similar to those of andalusite; indeed, apart from the symmetrically-disposed inclusions, chiastolite differs neither chemically nor crystallographically from andalusite. These minerals pass, by alteration, into kaolin. Andalusite also becomes changed into fibrous and scaly aggregates of muscovite or sericite.

Sillimannite,—$Al_2 O_3 Si O_2$,—occurs chiefly in extremely thin and needle-like prisms, often appearing of excessively small dimensions, even under very high powers. The most common form is that of the rhombic prism ∞P (110), with an angle of 111°.

Pinacoids are occasionally developed; but the crystals, beyond sometimes tapering to a point, either possess no terminations, or are too small to show them. Fine striation, parallel to the vertical axis, is occasionally visible.

The cleavage is parallel to the macropinacoid, but is only perceptible in the larger crystals. The prisms are also transversely traversed by small cracks, usually at comparatively wide intervals.

Sillimannite is colourless when viewed by ordinary transmitted light. The double-refraction is strong and positive, and the colours in polarized light are vivid, ranging as high as the middle of the second order. The optic-axial plane is situated in the macropinacoidal section, and the acute bisectrix is $\mathfrak{c} = c$. Consequently $a = \mathfrak{b}$ and $b = \mathfrak{a}$.

Hence, in parallel polarized light, when a prism of sillimannite lies with its longest axis at 45° to the principal sections of the Nicols, and a quartz wedge is inserted, also in that direction, a rise in colour will be seen in the crystal, the blue of the second order, for instance, appearing in the lower region of the first order, or close to the thin edge of the quartz-wedge.

In andalusite, which is optically negative, the effect would be reversed, so that we have, here, a means of distinguishing this mineral from sillimannite, basal sections of the latter showing an interference-figure in convergent light, the apparent optic-axial angle 2 E in air being 44° for red, and 37° for blue light.*

Pleochroism is not perceptible in the microscopic crystals.

Sillimannite is a mineral of frequent occurrence in gneiss and other crystalline schists. It is also a common product of the alteration of dichroite.

Fibrolite is apparently the same mineral. By alteration, sillimannite passes into kaolin.

Natrolite (Mesotype).—$Na_2 Al_2 Si_3 O_{10} + 2H_2O$. The crystals are commonly combinations of ∞P (110) and P (111); frequently, with brachypinacoids, $\infty \breve{P} \infty$ (010). In thin sections of rocks it usually appears in divergent or radiate groups and aggregates of minute needle-like crystals, which show a dark cross in parallel polarized light between crossed Nicols, the directions of maximum extinction lying parallel and at right angles to the longest, or vertical axis *c*, which is also the axis of least elasticity. The optic-axial plane lies in the brachydiagonal section; hence the double refraction is positive, and $a = \mathfrak{a}$, $b = \mathfrak{b}$, $c = \mathfrak{c}$. The apparent optic-axial angle in air is over 90°, and the dispersion is $\rho < v$. The cleavage is prismatic, but not perceptible in microscopic crystals.

Natrolite is essentially a decomposition product after nepheline, triclinic felspars, sodalite, haüyne, nosean, etc., and

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* An interesting study, by M. Lacroix, of the association of sillimannite with andalusite, in a specimen from Ceylon, will be found in the "Bulletin de la Société Française de Minéralogie" t. xi. p. 150, the two minerals having crystallized simultaneously. A section tangential to the obtuse angle formed by the prismatic cleavages of the andalusite shows three orientations of the included sillimannite with reference to the andalusite, viz.:—*c* parallel to *c*, *c* at 90° to *c*, and *c* at 45° to *c*. The same author also mentions a similar association in specimens derived from Morlaix in Brittany.

is to be met with in volcanic and other eruptive rocks in which those minerals occur.

Talc,—$Mg_3\,Si_4\,O_{11}+H_2O$,—usually occurs in scales, which, seen edgewise in rock-sections, bear a resemblance to fibres; or in thin plates with rounded or hexagonal boundaries, the latter resulting from the combination of 0 P (001), with ∞ P (110), and ∞ P ∞ (010). The scales are often arranged in divergent fan-like groups or rosettes.

The cleavage of talc is basal and very perfect, and gives rise to well-defined parallel lines in sections normal or oblique to the basal planes.

By transmitted light it appears colourless. The index of refraction is low. The double-refraction is negative, very strong, and the colours in polarized light are consequently high.

The optic-axial plane is parallel to the macropinacoid, and the acute bisectrix is parallel to, or coincides with, the vertical crystallographic axis; hence, $a=\mathfrak{b}$, $b=\mathfrak{c}$, $c=\mathfrak{a}$. The optic-axial angle is rather small. Even in a tolerably thick cleavage plate, the interference-figure shows, in convergent light, only a single system of elliptical rings, and comparatively small separation of the hyperbolæ, Fig. 93. The figure is often considerably distorted. The flesh-coloured blowpipe-reaction, when talc is moistened with a drop of solution of nitrate of cobalt, serves to distinguish this mineral from muscovite. Talc occasionally occurs pseudomorphous after enstatite and other magnesian silicates, but it is only met with in small quantity

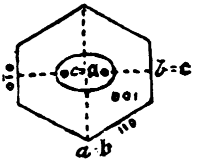

FIG. 93.

in eruptive rocks. It is chiefly found in crystalline schists, notably in talc-schist.

Anhydrite,—$Ca\,SO^4$,—The crystals are usually combinations of the prism ∞P (110), with the macro- and brachy-pinacoids and basal planes.

There are three cleavages, at right angles to one another, respectively parallel to the macro- and brachy- pinacoids and the basal planes. Generally, however, anhydrite occurs massive, or in granular and fibrous aggregates. Twin lamellæ are often seen traversing the granules diagonally to two of the rectangular cleavages.

By transmitted light, anhydrite appears colourless. The double-refraction is positive. The optic-axial plane lies in the brachydiagonal section; and the acute bisectrix is the axis of least elasticity, $\mathfrak{c}$, which coincides with or is parallel to the brachydiagonal a. Hence, $a = \mathfrak{c}$, $b = \mathfrak{b}$, $c = \mathfrak{a}$. Cleavage plates, parallel to the macropinacoid, give an interference-figure in convergent light. This is, however, the direction of least distinct cleavage. The apparent optic-axial angle, $2E = 71° 10' \text{ to } 71° 20'$.

Anhydrite very commonly becomes altered into gypsum by taking up water.

Aragonite,—$Ca\,CO_3$,—sometimes occurs as an alteration-product in certain eruptive rocks. Under these circumstances, it is chiefly met with in crystalline aggregates, which often exhibit a radiate or divergent prismatic structure. In thin sections aragonite appears colourless by ordinary transmitted light, and, owing to the absence of colour, it also shows no pleochroism. The double refraction is negative and very strong. The optic-axial plane lies in the macrodiagonal section, and the acute bisectrix is parallel to the vertical axis. Hence, $a = \mathfrak{b}$, $b = \mathfrak{c}$, $c = \mathfrak{a}$. In convergent light, basal sections show an interference-figure, and, in large crystals, sometimes two, owing to twinning. The optic-axial angle $2V = 18°$ for sodium light.

MONOCLINIC SYSTEM.

The crystals of this system are symmetrical to one plane only. Cleavages may occur both parallel and at right angles to this plane of symmetry; but if a crystal possess cleavages in both of these directions, they will not be equally perfect. Cleavage may also occur parallel to the basal planes and to the orthodomes. Each of these cleavages takes place in a single direction only, and they are consequently termed *monotomous*.

Monoclinic crystals may also present two other directions of cleavage, each parallel to opposite faces of the oblique rhombic prism, and both of equal intensity. Such prismatic cleavages make similar angles with regard to the plane of symmetry.

We may tabulate these possible directions of cleavage in monoclinic crystals in the following manner:—

Single Directions of Cleavage.

Pinacoidal . ∞Ᵽ∞ = 010 . ∞₽∞ = 100 . 0P = 001.
Orthodomous ₽∞ = $\bar{1}01$. 2₽∞ = $\bar{2}01$.

Double Directions of Cleavage.

Prismatic . ∞P = 110 and $1\bar{1}0$.

The pinacoidal planes of cleavage cut one another in such a manner that those parallel to 010 and 100 intersect at right angles on the basal pinacoids; while those parallel, 010 and 001, intersect at right angles on the orthopinacoids, or on sections parallel to those faces. The cleavage-planes parallel to 100 and 001 intersect upon the clinopinacoids at an angle corresponding with the inclination of 001 to 100, this angle being different in different mineral species.

The prismatic cleavage-planes intersect upon the basal pinacoids at an angle approximating to, but somewhat less than, the angle of the prism for any particular species; while in sections taken at right angles to the vertical axis, their angle of intersection will be precisely that of the prism. The cleavage planes parallel to the prism and to the clino- and ortho- pinacoids, give rise to striations or fine splits, all of which are parallel to the vertical axis.

It has been already mentioned (p. 48) that in the monoclinic system one of the axes of elasticity coincides with, or is parallel to, the orthodiagonal axis, or axis of symmetry, b, while the two remaining axes of elasticity lie in the symmetral plane. If the axis of mean elasticity $\mathfrak{b} = b$, then the optic axes and their bisectrices will be situated, and also be dispersed, in the plane of symmetry. In such a case the dispersion would be *inclined,* and the optic axes would be said to have a *symmetric position,* as shown in Fig. 45, p. 80.

If, on the other hand, either the acute or the obtuse bisectrix coincide with the orthodiagonal, the optic axes will then lie in a plane of the orthodiagonal zone, as indicated in Figs. 46, p. 80, and 47, p. 81, when, if the orthodiagonal be the obtuse bisectrix, the dispersion will be *horizontal,* as in Fig. 46. If, however, the orthodiagonal be the acute bisectrix, the dispersion will then be *crossed,* as in Fig. 47. In either case the optic axes would be said to have a *normal-symmetric position.*

The *parallel extinction,* or *straight extinction,* occurring in sections taken in the ortho-diagonal zone, and the *oblique* extinction in sections parallel to the plane of symmetry, have already been sufficiently explained in the first part of this work.

Monoclinic Pyroxene Group.

The minerals of this group occur either in well-developed crystals of a long- or short- prismatic habit, or in irregularly-bounded crystals, grains, and aggregates of crystals and grains. In this, as in every other case where *crystals* and *grains* of the same mineral are spoken of, the molecular structure, together with the optical and other physical properties thereon dependent, are, of course, the same both in the grain and in the well-formed crystal. It must, therefore, be understood that these different terms are employed merely to express differences in external form.

In crystals of monoclinic pyroxene, the following forms are those of most common occurrence:— ∞ P (110) . ∞ ₱∞ (010) . ∞ ₱∞ (100) . P (11$\bar{1}$) . −P (111) . 2P (221) . ₱∞ (10$\bar{1}$) . and 0P (001).[1] Twinning is extremely common in crystals of monoclinic pyroxene, and usually occurs upon a plane parallel to the orthopinacoid; it is, consequently, in sections parallel to the clinopinacoids that the twinning is best seen. In such crystals numerous twin-lamellæ are frequently visible, running parallel to the plane of composition, which is also the plane of twinning. Fine striation parallel to the edge 001 : 010 has been noted by Teall in clinopinacoidal sections of monoclinic pyroxene in the Whin Sill of Tyne Head, in which, owing to twinning on the face 100, the two sets of striæ meet chevron-wise, making an angle of between 74° and 75° (= the angle β) with the plane of twinning on either side of that plane. Twinning also occurs parallel to the basal plane, in which case it is generally many times repeated, so as to produce a fine twin-lamellation parallel to 0P (001). The two types of twinning just mentioned are occasionally seen in the same crystal; the latter type is especially frequent in diallage and diopside. A less common type of twinning is on a face of the hemiorthodome −₱∞ (101).

A zoned structure is often met with in augite crystals, the zones being usually parallel to the crystallographic boundaries; but this is not always the case, as evidence sometimes occurs that the zonal growths have subsequently been formed around a corroded crystal, the nuclear portion then presenting an

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[1] It is desirable that the student should familiarize himself with these and other forms by the help of well-constructed models.

irregular outline. The zones frequently appear of different colours, and they may often differ slightly in chemical composition, owing to isomorphous substitution. A peculiar structure is now and then seen in augite crystals, which is known as the "hour-glass structure." Such crystals show four fields in parallel polarized light, the alternate fields displaying similar colours. The direction of maximum extinction in the alternate fields is the same, but these directions differ somewhat in the different pairs, as shown by the rectangularly crossed lines in Fig. 94. This structure is considered to be due to the subsequent in-filling of the spaces in a skeleton crystal.

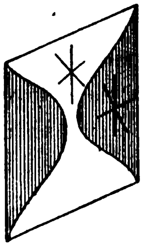

FIG. 94.

The cleavage in the minerals of this group is parallel to the oblique-rhombic prism ∞ P (110), the angle of the prism, and consequently that at which the cleavages intersect, being 87° 6′. The cleavage-planes therefore appear to cut one another nearly at right angles, in sections normal to the vertical axis, but in others more or less oblique to it, their intersections give rise to rhombic meshes, the angles of the rhombs varying according to the inclination of the section to the vertical axis. Sections parallel to the vertical axis merely show parallel fissures which are parallel to the vertical axis and to edges formed by faces of the prism with one another, and with the ortho- and clino- pinacoids. These cleavages are, however, seldom so well defined as in hornblende. In those crystals which are twinned on the basal plane, as diallage, there is generally a very distinct basal fission, which must nevertheless be considered due to the twinning, rather than to true cleavage.

By ordinary transmitted light sections of the monoclinic pyroxenes may appear colourless, of a greenish, yellowish, or brownish tint, or of deeper shades of green or brown, while occasionally a purplish or reddish tinge is perceptible. The pyroxenes vary in colour in rocks of different chemical composition; and, as pointed out by Rosenbusch, even in the same rock, differences in colour may be detected in pyroxenes which have not been all formed at the same time. And he sums up the colour-question by stating that the monoclinic pyroxenes, when they occur in rocks rich in silica and alkalies, are for the most part green; that in basic rocks and those poor in alkalies, they are usually brown; while in schists they are generally colourless or greenish. An examination of an extensive series of these rocks will show how just these conclusions are. The green crystals, when artificially heated, frequently change colour, owing to the peroxidation of the ferrous oxide which they contain, and become red or brownish red.

In all monoclinic pyroxenes the refractive index is high, and the double refraction positive and strong.

The optic-axial plane is situated in the plane of symmetry. The inclination of the bisectrices to the vertical axis is very variable, as also is the optic-axial angle; but the axis of least elasticity, *i.e.*, the acute bisectrix, nearly always lies in the obtuse angle, or angle β, formed by the vertical and clino-diagonal axes. The oblique extinction $c : \mathfrak{c}$ attains its maximum at an angle of 36° 30′ to 54° with the vertical axis. This observation, of course, can only be made with accuracy in sections parallel to the clino-pinacoids. The angles of maximum extinction are, however, in those crystals which possess a zoned structure, often found to differ in the different zones, and this is attributed to variation in chemical composition. That chemical composition has a marked influence on the obliquity of extinction, is now generally conceded, since it is found that in those monoclinic pyroxenes which are poor in ferrous oxide and alumina, as in diallage and diopside, the extinction-angle $c : \mathfrak{c}$ seldom exceeds 40°, while in the typical augites it very commonly ranges from 43° to 48°, and exceptionally attains, or even exceeds, 54°.

In the monoclinic pyroxenes, sections in the orthodiagonal zone show either entire or partial interference-figures in convergent light. For instance, if normal to the acute bisectrix, the two systems of rings will be visible; if normal to an optic axis, one system of rings; while other sections in this zone may show only a dark cross, one bar of which will correspond to a bisectrix. Sections normal to the acute bisectrix show the inclined dispersion. Pleochroism is, as a rule, barely perceptible in thin sections of monoclinic pyroxenes, affording generally, at best, only slightly different shades of green, yellow, or brown. There are, however, many exceptions, as in the augite crystals in trachytes, andesites, etc., where $\mathfrak{a}$ and $\mathfrak{c}$ give greenish, and $\mathfrak{b}$ brownish-yellow to reddish tints; while in the augites of basalts, and some other basic rocks rich in titaniferous iron, the axis colours for $\mathfrak{a}$ and $\mathfrak{c}$ are frequently yellowish, and for $\mathfrak{b}$ violet. The violet and reddish-brown colours generally indicating, according to Knop, that the pyroxene contains a certain amount of titanic acid. The usually weak pleochroism of the monoclinic pyroxenes generally serves, however, as a useful, although not an absolutely trustworthy, distinction between these minerals and the monoclinic amphiboles in which the pleochroism is very strong.

The specific gravity of the minerals of the former group being generally somewhat higher than that of the latter, renders the mechanical separation of the minerals of the one group from those of the other possible.

The chemical composition of the minerals of the Monoclinic Pyroxene Group may be expressed by the general formula $R'' Si O_2$, in which $R = Mg, Ca, Fe$, or Mn. Al_2 and Fe_2 are also frequently present; and, in some cases, K_2 or Na_2.

Malacolite includes the non-aluminous varieties of monoclinic pyroxene, or those which are essentially poor in alumina. They commonly contain 5 to 15 per cent. of ferrous oxide. The crystals are long-prismatic in habit; and, in addition to the usual prismatic and pinacoidal cleavages parallel to the vertical axis, they are generally traversed by strongly-defined cracks, which cross the crystals at right angles to the vertical axis. Along these cracks, decomposition-products of a serpentinous character are frequently developed, in the form of greenish fibrous growths, the fibres standing at right angles to the walls of the cracks. This is the beginning of the alteration, and commonly results in the separation of the crystal into distinct pieces, which still preserve their relation to one another, like the blocks of a fallen and disjointed column. Eventually the entire crystal passes into serpentine. In convergent light the optic-axial plane in malacolite will be seen, in suitable sections, to lie parallel to the length of the prism, and to the corresponding cleavage striæ; and this serves to distinguish the mineral from epidote, in which the optic-axial plane lies at right angles to the length of the crystal and to the cleavage striæ. In both minerals, however, the optic-axial plane is in the plane of symmetry, and the apparent difference in its situation is due to excessive development of the epidote crystals in the direction of the ortho-diagonal, and to the striæ of these crystals being produced by basal cleavage-planes. Malacolite chiefly occurs in crystalline schists, gneiss, etc., and is of comparatively rare occurrence in eruptive rocks. The granular variety, coccolite, is met with mostly in altered limestones, as in that of Tiree.

Diallage.—It is very rarely that *crystals* of diallage are seen. In the few cases in which they have been found, the orthopinacoids are the dominant faces. As a rule, diallage presents no definite crystallographic boundaries other than orthopinacoids and cleavage planes parallel to those faces. A prismatic cleavage is also frequently shown, but it is far less perfect than that parallel to the orthopinacoid. Occasionally still less satisfactory cleavages are met with parallel to the clinopinacoids and to the basal planes. The pinacoidal separation-planes are considered by Rosenbusch to be due rather to twinning, giving rise to a platy or lamellar structure, than to true cleavage dependent upon original differences of cohesion. Tschermak has, however, found these planes to vary as much as 15° from the orthopinacoid (100).

Diallage commonly shows a fibrous or rod-like structure. The colour is greyish-green, green, or brownish. The double refraction is strong, and the axis of least elasticity makes an angle of 39° 41′ with the vertical axis. The optic-axial plane lies in the plane of symmetry, as in other monoclinic pyroxenes; and cleavage plates of diallage (parallel to 100) show one of the systems of polar rings in convergent light. This axial interference-figure in cleavage plates of diallage serves to distinguish them from those of enstatite, or other rhombic pyroxenes. It is common, however, to find numerous lamellæ of the latter minerals enclosed in diallage. These included plates are generally very small; but when of sufficient size to admit of observations in convergent light, they show a dark cross, one bar of which corresponds with a bisectrix. It must be remembered, however, that these are *included crystals*, and not cleavage plates.

Diallage becomes altered into serpentine, frequently with some admixture of chlorite, epidote, or calcite. This change is engendered by the usual processes of weathering; but in other cases, as in certain gabbros, diallage is found to be converted into amphibole.

Augite varies considerably in chemical composition, but may, in the main, be regarded as an admixture of $Mg\,Al_2\,Si\,O_6$ with $Mg\,Fe_2\,Si\,O_6$ in variable proportions, while, at times, there is isomorphous substitution of the molecule $Na_2\,Fe_2\,Si_4\,O_{12}$. Augite occurs as a rock-constituent, both in well-developed crystals and in crystalline grains or crystals, which show no definite crystalline faces, but merely irregular boundaries, such as have been enforced by the crystallization of the surrounding minerals (allotriomorphous crystals) also, but rarely, polysomatic, as noted by Lawson in certain dykes of diabase, several crystals being grouped together with different orientation, but not twinned. The well-formed crystals are generally combinations of ∞ P (110) . ∞ Ᵽ ∞ (010) . ∞ Ᵽ ∞ (100) . P $(11\bar{1})$. – P (111) . Ᵽ ∞ $(10\bar{1})$ and 0P (001). Twin crystals are common, and the twinning is upon a plane parallel to the orthopinacoid ∞ Ᵽ ∞ (100). Sections parallel to this face do not therefore show the twinning, but in those parallel to the clinopinacoid (010) and the prism (110) it is distinctly seen. A zoned structure, due to the successive growth of layers, which differ more or less in composition through isomorphous substitution, is frequently met with in augite crystals. The cleavage is parallel to ∞ P (110) and to ∞ Ᵽ ∞ (100); but the former, although at times it is clearly visible in basal sections, or in sections transverse to the prism, is at others very obscure or quite imperceptible. When this cleavage appears, it can easily be distinguished from that of hornblende by the planes, which are often interrupted, intersecting nearly at right angles (87° 6′); while in hornblende the angle is about thirty-three degrees wider, and the difference can, therefore, be detected at a glance. The cleavage parallel to the orthopinacoid is much less strongly marked than in diallage, and, as already indicated, it seems that this cleavage becomes more accentuated in proportion to the alteration that the diallage may undergo. It is indeed very probable that diallage is merely a somewhat altered condition of augite.

Sections of augite appear green or brown, as a rule, by transmitted light; but they occasionally exhibit various shades of brownish-red, yellow, or violet. When very thin, they sometimes look almost colourless, or of a very pale greenish, yellowish, or brownish tint. The oblique extinction angle $c : \mathfrak{c}$ is generally over 40°, and occasionally reaches 54°.

The double refraction is positive and strong, and the colours seen in polarized light are brilliant. Sections parallel to the orthopinacoid (100) show one of the systems of optic-axial rings in convergent light; and sections at right angles to the vertical crystallographic axis do the same. The relative positions of the optic axes, bisectrices, etc., are shown in Fig. 95, which represents one of the most common combinations. Inclusions of apatite, mica, olivine magnetite, ilmenite, etc., are common in augite. Fluid lacunæ and inclusions of liquid carbonic acid are also tolerably frequent.

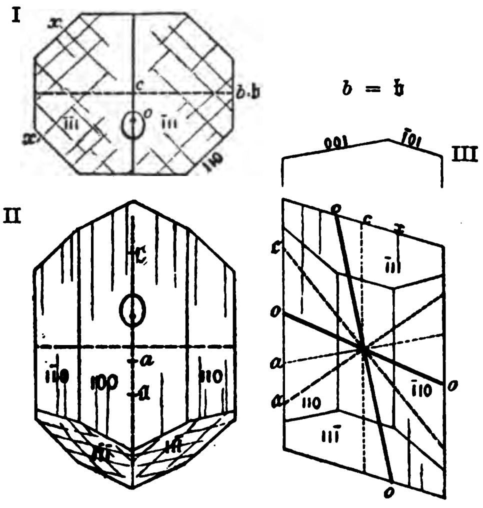

Fig. 95.

When zonal structure is present, the optical characters usually vary to some extent in the different zones.

Occasionally intergrowths of augite and hornblende are seen; and under these circumstances the plane of symmetry is the same for both minerals, and they also have the vertical axis in common.

Augite becomes altered into chlorite, epidote, greenearth, serpentine, etc., and it also, at times, shows the well-known paramorphic conversion into hornblende, the result being termed Uralite. In this the original form of the augite crystal remains; but the hornblendic paramorph shows the cleavage planes of hornblende, which, intersecting at about 124°, are, of course, not parallel to the prism faces of the original augite.

Augite is an important constituent of a large number of basic rocks, such as basalts, andesites, etc.; and crystals, either entire or broken, are extremely common in volcanic tuffs.

Omphacite is a variety of augite met with in a rock called eclogite. The mineral seldom or never shows any definite crystalline faces, but occurs in rounded or irregularly-shaped grains of a clear green colour. These often exhibit an intergrowth of smaragdite, a variety of hornblende, both minerals having in this case a common vertical axis and symmetral plane. Omphacite does not appear to differ in any essential respect from augite, or rather, perhaps, from diallage, except in tint, the name being derived from *ὄμφαξ*, an unripe grape. Minute crystals of rutile frequently occur as inclusions in omphacite.

Acmite is a species of monoclinic pyroxene rich in soda, the formula being $Na_2\ Fe_2\ Si_4\ O_{12}$. The crystals, when perfectly formed, have extremely acute terminations; but these are seldom seen in rock-sections, where the faces developed are the prism ∞P (110) and the orthopinacoid, $\infty \bar{P} \infty$ (100). Clinopinacoids, if present, are quite subordinate, but they are nearly always absent. The faces in the prism zone are strongly striated parallel to the vertical axis. Sometimes the mineral occurs in grains. There are well-marked cleavages parallel to ∞P, intersecting at 87°. The crystals are usually twinned on the orthopinacoïd, and frequently show parallel intergrowths of augite or hornblende. The principal cleavage is parallel to the faces of the prism ∞P. By reflected light the crystals appear blackish-brown, by transmitted light, green, brown, or brownish-yellow.

The double refraction is very strong. The optic-axial plane lies in the plane of symmetry. The character of the double refraction is not yet fully determined, but it is regarded as negative.

The axis of greatest elasticity $\mathfrak{a}$, probably the acute bisectrix, lies in the acute angle formed by the vertical and the clinodiagonal axis, and makes with the former an angle of 4° to 5°, the mutual inclinations of the directions of maximum extinction in adjacent twin-lamellæ, therefore, make an angle which varies from 8° to 10°. The pleochroism is very strong, $\mathfrak{a}$ = dark-brown to greenish-brown, $\mathfrak{b}$ = clear-brown to yellow. $\mathfrak{c}$ = greenish-yellow. The absorption is $\mathfrak{a}>\mathfrak{b}>\mathfrak{c}$, $\mathfrak{a}$ lying nearly parallel to the vertical axis, or length of the prism. This mineral fuses easily, colouring the flame yellow.

Aegirine, which is closely related to acmite, has usually a rather greater angle for the oblique extinction, and differs somewhat from acmite in the pleochroism. $\mathfrak{a}$ = chestnut brown, $\mathfrak{b}$ = olive-green, $\mathfrak{c}$ = grass-green. The axis-colours here given for acmite and aegirine are, however, not invariably met with, specimens from different localities often showing different colours. By reflected light aegirine always appears, according to Brögger, of a *blackish-green,* while, by similar illumination, acmite looks *blackish-brown.* Both acmite and aegirine occur in elæolite-syenites. They are also met with in certain phonolites, trachytes, leucitophyres, etc.

Although differing considerably from the true pyroxenes in chemical composition, there are one or two monoclinic rock-forming minerals, such as Spodumene and Wollastonite, which are to some extent related to them.

Spodumene,—$Li_2\ Al_2\ Si_4\ O_{12}$,—occurs as an accessory mineral in certain granites and crystalline schists. The cleavage, as in acmite, is parallel to ∞ P (110) the planes intersecting at an angle of 87°; and there is in addition a very distinct cleavage parallel to the ortho- and an imperfect one parallel to the clino- pinacoid. In optical characters spodumene resembles diopside.

By alteration spodumene undergoes the peculiar changes described by Brush and Dana. These consist in the first place of a change into what is called β spodumene, which is a mixture of albite and a substance termed eucryptite, the latter having the composition $Li_2\ Al_2\ Si_2\ O_8$. In β spodumene a slightly fibrous structure is seen, the fibres lying normal to the surfaces of the crystal. In sections of β spodumene cut parallel to the fibrous structure, the latter is seen to be due to fibres of eucryptite included in the albite, while, in sections at right angles to the fibrous structure, the eucryptite appears in more or less hexagonal bands or borders, which resemble the markings seen in graphic granite, or micropegmatite (Fig. 96).

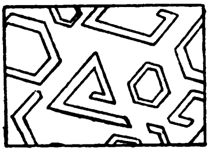

Fig. 96.

The alteration of spodumene into β spodumene results from an exchange of sodium for half of the lithium present in the unaltered mineral.

The next phase of alteration consists in the substitution of potassium for the lithium in the β spodumene; in other words, the eucryptite, or lithium-bearing portion of the β spodumene, is converted into muscovite or potash-mica, so that this final alteration-product consists of muscovite and albite, the mixture being known as cymatolite. In this a very fine fibrous structure exists, except in extreme cases, when the two minerals segregate into distinct layers of muscovite and layers of albite.

These changes are best studied, not in crystals of microscopic dimensions, but in large ones, such as those occurring in Connecticut and Massachusetts, where crystals of spodumene have occasionally been found measuring nearly four feet in length, a foot in breadth, and two to four inches in thickness.

Wollastonite,—$Ca\,SiO_3$,—occurs as a rock-forming mineral chiefly in imperfectly-developed rod-like or platy crystals, or in aggregates of such crystals, in which either a parallel or feebly divergent arrangement is seen. The crystals are always much elongated on the orthodiagonal axis b.

The forms chiefly developed are $0\,P\,(001)$; $\infty\,\bar{P}\,\infty\,(100)$; $\frac{1}{2}\bar{P}\,\infty\,(10\bar{2})$ and $-\,\bar{P}\,\infty\,(101)$.

The basal planes dominate, from which circumstance the mineral is also known as table-spar. Twinning on the orthopinacoid is common, the basal planes then making an angle of 169° with one another.

There is a perfect basal cleavage, and a less distinct one parallel to the orthopinacoid. The cleavage-planes in these two directions intersect at 95° 30′, in sections parallel to the clinopinacoid. By transmitted light, the mineral appears colourless.

The optic-axial plane lies in the plane of symmetry, and the acute bisectrix $\mathfrak{c}$ is in the obtuse angle β. In sections normal to the bisectrix inclined dispersion is distinctly seen in convergent polarized light. The mineral shows no pleochroism.

It is chiefly met with in granular limestones, gneiss, crystalline schists of various kinds, garnet-rock, epidosite, etc. It is seldom seen in truly eruptive rocks.

Monoclinic Amphibole Group.

In this group the crystals, although a short-prismatic habit is common, show, as a rule, a stronger tendency to a long-prismatic habit than those of the monoclinic pyroxene group. Crystals of the so-called basaltic hornblende are generally well terminated, but those of actinolite and of common hornblende are often irregularly jagged, or appear to be frayed out at the ends. This is especially common in the smaller crystals and microliths, which frequently resemble worn-out paint-brushes at their extremities. Sometimes the crystals are seen to be composed of a great number of microliths lying side by side; an arrangement which may offer a rude approximation to the asbestiform or byssolitic condition of amphibole.

Among the well-developed crystals, the most common forms are the oblique-rhombic prism, ∞P (110), with an angle of about 124° 30′, the clinopinacoid, ∞ Ꝑ ∞ (010), the pyramid P $(\bar{1}11)$ and the basal plane 0 P (001). The clinodomes Ꝑ ∞ (011) are also faces of very frequent occurrence; but the orthopinacoids are rather uncommon, and, consequently, sections of hornblende transverse to the vertical axis usually present more or less hexagonal outlines, while the corresponding sections of augite are generally octagonal. Stalk-like or reedy forms are likewise of frequent occurrence, and occasionally the amphibole in a rock is merely represented by irregular grains. This is, however, not usual.

The twinning occurs upon a plane parallel to the orthopinacoid, as in augite. In the more common combination this has the effect of bringing all the pyramid faces to one extremity of the crystal and the two basal planes to the other, a phenomenon very usual in crystals of basaltic hornblende. Such twins show no re-entering angles. A number of delicate parallel twin lamellæ are frequently developed between the two larger halves of the twin. Zonal growths are sometimes seen in amphibole.

There is always a perfect cleavage parallel to faces of the prism ∞P (110) which is well seen in sections at right angles to the vertical axis, the cleavage planes intersecting at an angle of 124° to 125°. In all sections parallel to the vertical axis these cleavage planes appear as parallel lines, for, even if the section be parallel to one of the directions of cleavage, it will be scored by the prismatic cleavage cracks which lie in the other direction, *i.e.*, a section parallel to the faces 110 and $\bar{1}\bar{1}0$ will be striated by the cleavage cracks parallel to $1\bar{1}0$ and $\bar{1}10$, just as in the case of any section in the prism-zone of a crystal which possesses prismatic cleavages in two directions. In some few instances very imperfect cleavages are found parallel to the clinopinacoid.

As a rule, in transmitted light, thin sections of monoclinic amphibole appear green or brown of various shades, according to the depth of colour which the crystal possesses and according to the thickness of the section. In glaucophane, however, the colour is blue, while tremolite appears colourless. Actinolite is always green; basaltic hornblende brown or reddish-brown, while in common hornblende the colour is almost always green. The colour, however, may be changed from green to red or brown by heating, the ferrous oxide in the amphibole passing into ferric oxide. It is thus that the pale-green fern-like belonites in the Arran pitchstone become, when the rock is artificially heated, of a deep reddish-brown colour.

The refractive index of the monoclinic amphiboles is high. The double refraction is strong, and usually, but not invariably, negative. In the variety *pargasite,* for instance, it is notably positive.

The optic-axial plane is in the plane of symmetry. The optic-axial angle is very variable. The axis of least elasticity, $\mathfrak{c}$, lies in the acute angle formed by the clinodiagonal and the vertical axis, and makes with the latter an angle which may vary from 0° to 27° or more. No definite relation between the chemical composition and the angle $c : \mathfrak{c}$ has yet been satisfactorily made out.

The measurement of the oblique extinction angle in cleavage-plates parallel to ∞P (110) is necessarily much smaller than the true angle, which would be found in sections parallel to $\infty \rlap{\backslash}P \infty$ (010). But an approximation to the real angle may be procured by adding half as much again to the angle measured in a cleavage-plate parallel to ∞P.

Sections taken in the orthodiagonal zone give interference-figures, entire or partial, in convergent polarized light. If normal to the bisectrix, both polar rings will be visible; if normal to an optic axis, only a single system of rings; while in other directions in this zone a more or less oblique ring-picture will be procured, or the dark bars corresponding to a bisectrix and an optic normal.

Cleavage-plates parallel to ∞P (110) show a single system of rings lying near the margin of the field of the polariscope or microscope. All monoclinic amphiboles which possess any colour are more or less strongly pleochroic.

Those of a pale green colour may have their pleochroism rendered more distinct by being artificially heated to redness on platinum foil. The absorption is always greater for the vibrations parallel to the axis of least elasticity, $\mathfrak{c}$, than for those parallel to that of greatest elasticity, $\mathfrak{a}$.

The following are the chief rock-forming varieties of monoclinic amphibole.

Amphiboles containing little or no alumina.

Tremolite,—$Ca\,(Fe, Mg)_3\,Si_4\,O_{12}$,—is a colourless variety of amphibole occurring in slender prisms ∞P (110), usually much fissured by irregular transverse cracks. The prisms seldom or never show any terminal faces, but either end abruptly or split up into fibres. Ordinary asbestus is, in fact, a variety of tremolite in which the structure is essentially and completely fibrous. Platy forms are also met with.

The cleavage in the larger crystals is well defined and parallel to faces of the prism. The double refraction is strong.

Tremolite occurs in beds of limestone and dolomite, associated with crystalline schists. In serpentines it usually appears as an alteration-product, while in certain basic rocks containing olivine it has been found as a secondary mineral forming envelopes around the olivine crystals. Tremolite itself becomes altered into talc.

Actinolite differs from tremolite in containing from 5 or 6 to 12 or 13 per cent. of ferrous oxide, which imparts a more or less distinct green colour to it. Apart from this colour and the consequent pleochroism, there is but little difference crystallographically between this mineral and tremolite.

The slender prisms of actinolite usually form divergent or radiating groups, hence the name. The crystals, in addition to the prismatic cleavage, sometimes show one parallel to the clinopinacoid. Like those of tremolite they never exhibit any terminal faces and are also strongly cracked transversely to the prism. Fibrous and reed-like aggregates are not uncommon.

The individuals vary considerably in dimensions, some being an inch or two in length while others are microscopic; but, in all, the same slender prismatic habit is noticeable. The feebly-coloured varieties scarcely show any pleochroism, but in those which are more strongly coloured it is quite distinct, being often clear green parallel to $\mathfrak{c}$, and yellowish-green parallel to $\mathfrak{a}$ and $\mathfrak{b}$. The absorption is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$, or $\mathfrak{c} > \mathfrak{b} = \mathfrak{a}$.

Actinolite mostly occurs in the crystalline schists, associated with talc, chlorite, epidote, pyroxene, etc., and it is the chief constituent of actinolite schists. It is also a common alteration-product in eruptive rocks.

The emerald-green variety known as smaragdite is met with in the saussurite-gabbros, in which it frequently appears in the form of diallage, and is probably to be regarded as a paramorph after that mineral.

It is not certain whether the so-called smaragdite in the rock known as eclogite should be referred to actinolite or to common hornblende.

The *jade* of China and the Pacific Islands is, in part, referred by Damour to smaragdite; but most of the jade or nephrite is regarded as a matted fibrous variety either of tremolite or actinolite.

Amphiboles containing Alumina.

Hornblende.—*Common Hornblende.* The chemical composition of common hornblende, basaltic hornblende, and other varieties, is difficult to express precisely by means of formulæ. These minerals may, however, be regarded, according to Tschermak, as isomorphous mixtures of the molecules $Ca\,Mg_3\,Si_4\,O_{12}$; $CaFe_3Si_4O_{12}$; $Na_2Al_2Si_4O_{12}$, and another molecule of an aluminous silicate of which the composition is not yet exactly known. Common hornblende appears usually of a distinctly green colour by transmitted light, rarely brown or brownish red.

Fig. 97 shows the relation of the optic axes and axes of elasticity to the crystallographic axes, pinacoidal faces, and prismatic cleavages.

The extinction angle $c : \mathfrak{c}$, as measured in cleavage-plates of common green hornblende parallel to the prism ∞ P (110), is 13° or more. In common brown hornblende it ranges from 13° to 0°. The pleochroism in the green hornblende is very distinct; frequently $\mathfrak{a}$ = yellow, $\mathfrak{b}$ = brownish-green, $\mathfrak{c}$ = bluish-green; in the brown, $\mathfrak{a}$=yellowish or greenish, $\mathfrak{b}$ and $\mathfrak{c}$= different tints of brown. The pleochroism is generally stronger in the brown than in the green varieties.

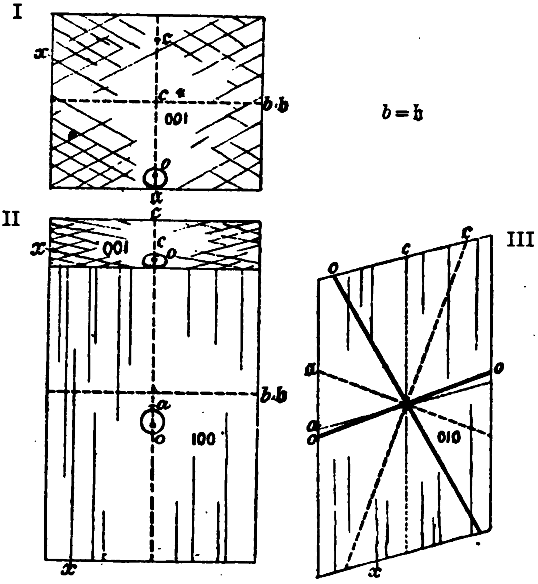

Fig. 97.

Common hornblende occurs chiefly in syenites, diorites, gneiss, amphibolites, and various crystalline schists.

In some of these rocks the hornblende occasionally appears in a condition known as reedy hornblende "*schilfige hornblend.*" Rosenbusch regards this as an altered or uralitized condition of augite, and considers it to be more closely allied to actinolite than to common hornblende. This reedy hornblende appears in aggregates of approximately parallel rods or fibres of a clear green colour and feebly pleochroic. Rosenbusch also suggests that reedy hornblende may, in some instances, be developed by the splitting up of a crystal of ordinary hornblende through the partial conversion of the crystal into chlorite along the cleavage-planes.

Basaltic Hornblende nearly always occurs in well-formed crystals which are combinations of ∞P (110), $\infty \not{P} \infty$ (010), P ($\bar{1}11$), and $0 P$ (001).

At times, however, the crystals appear more or less rounded or corroded by the action of the magma which surrounded them. The prismatic cleavage in these crystals is strongly marked. By reflected light they look black; by transmitted light even very thin sections appear of a deep brown or reddish-brown. Occasionally they show zonal growths of alternating green and brown colours. The pleochroism is extremely strong; $\mathfrak{a}$ = clear yellow, $\mathfrak{c}$ = dark-brown. The absorption is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$. The oblique extinction angle $c : \mathfrak{c}$ is small, and is sometimes *nil.*

Chlorite, calcite, dolomite, quartz, limonite, etc., occur as alteration products after both basaltic and common hornblende.

Amphiboles containing Soda.

These may be distinguished from other members of the group by their very easy fusibility.

Glaucophane,—$Na_2Al_2Si_4O_{12}$,—is a blue variety of monoclinic amphibole, and until quite recently has only been found sparsely disseminated in the crystalline schists of a few localities. It has, however, lately been met with as an important and prevalent constituent of certain Japanese rocks, which have been described by Kotô under the name of glaucophane schist. The crystals are prismatic in habit and in cleavage, the angle of the latter being the same as that in common hornblende. There is also a transverse fission, similar to that met with in actinolite. The oblique extinction-angle $c : \mathfrak{c} = 4°$ to 6°. Glaucophane exhibits strong pleochroism; $\mathfrak{c}$ = sky-blue or ultramarine-blue, rarely bluish-green; $\mathfrak{b}$ = violet; $\mathfrak{a}$ = yellowish-green or colourless.

The mineral is usually associated with actinolite, diallage, omphacite, epidote, etc. In the Japanese schists it is frequently accompanied by piedmontite (*mangan-epidot*).

Arfvedsonite,—$Na_2Fe_2Si_4O_{12}$,—occurs in the zircon-syenites of Scandinavia and Greenland. It resembles common hornblende in appearance. Only extremely thin flakes transmit light and show strong pleochroism. Krokydolite, a blue asbestiform condition of arfvedsonite, has been found by Delesse in metamorphosed limestone.

The well-known krokydolite catseye imported from Griqualand results, as shown by Renard and Klement,* from the infiltration of silica among the fibres of this mineral, the brown or golden-yellow colour of most specimens being due to hydration of the iron oxide in the krokydolite.

Mica Group.

The micas are characterized by the extensive development of the basal pinacoid 0 P (001), and by the perfect cleavage which they exhibit parallel to this plane, by their lustre, and by the approximation of their crystals to hexagonal and rhombic forms. In a cleavage-plate taken from a crystal of mica we have a six-sided table or film, of which four of the sides are boundaries due to faces of the oblique-rhombic prism ∞ P (110), and the remaining pair to clinopinacoids ∞ Ᵽ ∞ (010), as shown in Figs. 100 and 101. Faces of the pyramid P ($\bar{1}11$), and of $-\frac{1}{2}$ P (112), -2 P (221), and ∞ Ᵽ ∞ are also sometimes developed. Twinning is by no means uncommon, and occurs on several different types. Of these, one of the most prevalent is twinning upon a face of the oblique-rhombic prism ∞ P (110), the plane of composition or contact being the basal plane 0 P (001). By this method of twinning the clinopinacoids of one half of the twin do not correspond with those of the other half, as shown in Fig. 98, where the upper half is represented in the reversed position brought

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* Bull. Acad. Royale de Belgique. Ser. 3, vol. viii.

about by twinning, so that the basal plane $00\bar{1}$ occurs above as well as below the twin.

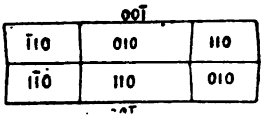

Fig. 98.

When crystals elongated in the direction of the axis *b* are twinned upon this type, re-entering angles are formed.

The student will best understand this kind of twinning, by cutting a piece of paper into two similar hexagons, and marking $\infty \bar{P} \infty$ upon two opposite edges in each. One of these hexagons should then be turned in the plane of (110); *i.e.*, in a plane at right angles to the surface of the other hexagon, and parallel to a pair of its unmarked edges. By subsequently cutting narrow strips off each of the unmarked edges, and turning as before, the formation of the re-entering angles will be readily understood.

As a rock-constituent the micas frequently occur in scales and flakes, which, when viewed at right angles to their broad surfaces or basal planes, are seen to have irregularly notched or ragged boundaries. Sections of such flakes and scales cut obliquely or at right angles to the base are, however, always bounded by the parallel faces of the basal planes, and consequently appear lath-shaped. Such sections also exhibit fine parallel striæ, which denote the basal cleavage. In the more perfectly-developed crystals the basal sections are hexagonal in form, although, occasionally, extension along the orthodiagonal axis produces very elongated six-sided forms. Sections of the well-developed crystals transverse to the base give lath-shaped forms similar to those of the less perfectly bounded plates and scales, except that the laths do not show splintery-looking ends. Even, however, in perfectly-bounded crystals a separation, or wedging apart, of the laminæ may sometimes be seen in these sections. Occasionally the crystals, and very frequently the thin flakes and scales, appear bent.

In some cases isomorphous intergrowths may be observed. These assume the form either of concentric zones which are conformable to the hexagonal boundaries of the crystal, or of alternating plates parallel to the basal planes.

The cleavage plates of mica may be distinguished from those of chlorite, talc, and some other minerals, which also exhibit perfect basal cleavage, by the elasticity of the mica plates, while those of the other minerals are, in some cases, brittle, in others flexible, but not elastic; *i.e.*, they either break or remain bent, and do not spring back to their original position.

If we place a plate of mica upon a smooth, but slightly yielding surface, such as a pad of paper or a slab of cork, and then drive a needle, by a sharp, springy tap with a piece of wood,* into the mica, we shall find, if the operation be dexterously performed, that, around the point where the needle entered, a small six-rayed star has been developed. The star consists of three straight cracks, one of which lies in the plane of symmetry, or parallel to the edge 001 : 010, while the two others lie respectively parallel to the edges 001 : 110 and $001 : 1\bar{1}0$ (Figs. 100 and 101). These cracks intersect at angles of 60°. The star is called a *percussion-figure.*

If we examine a mica plate, in which such a percussion-figure has been produced, in convergent polarized light, we shall see that the optic-axial plane of the mica lies either parallel to, or at right angles to the plane of symmetry. In other words, the line joining the two systems of rings in the

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* Sometimes better results may be procured by employing a blunt-ended punch and a small hammer. A fine needle working vertically on a little spring *ss*. Fig. 99, and driven by an adjustable watch-spring *w*, has been successfully used by Lattermann for producing percussion-figures in very minute scales of mica.

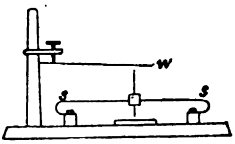

FIG. 99.

interference-figure * will be found to be either parallel to that ray of the star which lies in the plane of symmetry, as in Fig. 101, or at right angles to it, as in Fig. 100.

An important means is thus afforded of distinguishing certain species of mica from one another. Tschermak has found that, in this manner, the micas may be divided into two orders—the first order including those micas in which the optic-axial plane lies across the symmetral crack or guide-line of the percussion-figure, as in Fig. 94; while the second order includes those in which the optic-axial plane coincides with or is parallel to the guide-line.

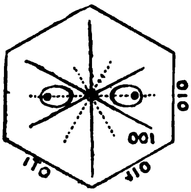

Fig. 100.

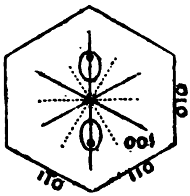

Fig. 101.

By *pressing* a blunt-ended punch on a mica-plate, a star may be produced, the rays of which lie in directions at right angles to the edges 001 : 010, 001 : 110, and 001 : 1̄10, as indicated by the dotted lines in Figs. 100 and 101. These are termed *pressure-figures.* They are seldom or never so sharply defined or so perfect as the percussion-figures. The rays of the pressure-figures usually look like frayed-out bundles of fine fibres, and frequently only three rays are developed, which are not continued beyond the point where the pressure is applied.

The following is a list of the principal micas, classified according to the direction of the optic-axial plane with reference to the plane of symmetry.

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* For the purpose of demonstration it is best to employ a mica in which the angle of the optic axis is considerable, such as muscovite.

1st Order.			2nd Order.		
Muscovites.	Muscovite	$\rho > v$.	Phlogopites.	Phlogopite	$\rho < v$.
	Lepidolite			Zinnwaldite	$\rho > v$.
	Paragonite				
Biotites.	Anomite	$\rho \gtrless v$.	Biotites.	Biotite	$\rho < v$.
				Meroxene	
				Lepidomelane	
				Rubellane	
				Anomite ?	

The refractive index of the micas is comparatively low. The double refraction is always negative and very strong, and the colours in polarized light brilliant. As shown in the preceding table, the optic-axial plane lies sometimes parallel to, at others at right angles to, the plane of symmetry. The angle of the optic axis is very variable, ranging from 0° in some of the biotites to about 80° in certain muscovites.

The acute bisectrix, which is also the axis of greatest elasticity, is frequently almost coincident with the vertical axis, the angle which it makes with it being sometimes barely appreciable; and it is seldom that this angle $c:\mathfrak{a}$ exceeds 9°. In consequence of this, cleavage-plates of mica always give an interference-figure in convergent light. This figure, although usually markedly biaxial in character, often appears, in micas of small optic-axial angle, as a single system of elliptical rings, while in those in which the angle of the optic axis is still less, the rings become so nearly circular and the separation of the hyperbolæ so slight and indistinct, that it is scarcely possible to distinguish them from the interference-figures of truly uniaxial crystals.

Owing to the acute bisectrix $\mathfrak{a}$ being practically at right angles to the basal plane, it is found that, in the micas of the first order, the obtuse bisectrix $\mathfrak{c}$ almost precisely coincides with the clinodiagonal, and the optic normal $\mathfrak{b}$ with the orthodiagonal axis; while in the micas of the second order, the obtuse bisectrix $\mathfrak{c}$ nearly coincides with the orthodiagonal, and the optic normal $\mathfrak{b}$ with the clinodiagonal axis.

We have consequently, for the micas of the first order, $a=\mathfrak{c}$, $b=\mathfrak{b}$, $c=\mathfrak{a}$, and in the second order, $a=\mathfrak{b}$, $b=\mathfrak{c}$, $c=\mathfrak{a}$, or almost so;* a condition which as nearly as possible agrees with that met with in rhombic crystals. In consequence of this, all sections of mica which are cut at right angles or obliquely to the basal planes show, between crossed Nicols, directions of maximum extinction which are practically parallel and at right angles to the traces of the basal cleavage planes. Occasionally a small oblique extinction-angle may be measured, but it is unusual to find any very appreciable deviation of the axes of elasticity from the crystallographic axes. The resemblance of the micas of the muscovite and phlogopite series to crystals of the rhombic system is very close. The biotites approximate more in their optical characters to minerals crystallizing in the hexagonal system. In the biotites the optic-axial angle is often so small as to be barely appreciable, and basal sections then appear isotropic in parallel polarized light between crossed Nicols, just as basal sections of hexagonal minerals would do. As the angle of the optic axes increases in the micas, the double refraction in the basal sections becomes more marked.

In all micas the luminous vibrations parallel to, are more strongly absorbed than those normal to the base. The absorption-difference may be quite well observed in the colourless micas, the difference being as great in colourless muscovite as it is in calcite.

In the coloured micas the pleochroism is very strong. Sections of the micas of the muscovite and phlogopite series

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* The student should remember that in monoclinic crystals $\mathfrak{a}$ and $\mathfrak{c}$ cannot really coincide with crystallographic axes: $b=\mathfrak{b}$ being the only coincidence of a crystallographic axis with an axis of elasticity.

appear colourless or of pale yellowish or greenish tints by ordinary transmitted light; but, from the presence of thin films of air between their cleavage laminæ, they often show iris-coloured bands and circles, as in Newton's rings. Sections of the biotites, on the other hand, usually exhibit deep green or brown colours, while some varieties, as rubellane, show dark reddish-yellow or orange tints.

The following is a brief description of the characters of the principal micas, commencing with those of small axial angle.

Biotite.—The micas of the biotite series are isomorphous mixtures of $K_2\ Al_2\ Si_2\ O_8$ (or the muscovite-molecule), with $Mg_2\ Si\ O_4$ (the typical olivine-molecule), the two molecules being in the relative proportions of 1 : 1 to 2 : 1.

In lepidomelane the alumina is more or less replaced by ferric oxide; and the magnesia in the micas of this series is often supplanted by varying amounts of ferrous or manganous oxides. Haughtonite is a mica especially rich in ferrous oxide. Twelve analyses of this species, by Heddle, showing a range of from 14 to over 19 per cent. of $Fe\ O$ with from 2 to above 7 per cent. of $Fe_2\ O_3$.

Under the name biotite are included the magnesian micas known as meroxene, lepidomelane, and rubellane. They all belong to Tschermak's second order, *i.e.*, the optic-axial plane coincides with, or is parallel to the plane of symmetry, also to the guide-line in the percussion-figure. The angle $c : a$ is usually very small, being at times, as already stated, scarcely perceptible. The optic-axial angle is very variable, but is frequently so small that the interference-figure assumes a uniaxial character. Tschermak has, however, met with biotites in which the apparent optic-axial angle was as much as 56°; and Rosenbusch states that it is occasionally somewhat higher, Lattermann having found $2E = 72° 30'$ in the biotite of a mica-andesite from Repistye, near Schemnitz.

The pleochroism of biotite is very strong, the rays vibrating parallel to $\mathfrak{b}$ and $\mathfrak{c}$,—which both lie in a plane parallel to the basal cleavage—being almost totally absorbed, as in the case of the ordinary ray in tourmaline; while that vibrating parallel to $\mathfrak{a}$ suffers only slight absorption.

The relative absorption of $\mathfrak{b}$ and $\mathfrak{c}$ varies. The general relation may be stated as $\mathfrak{c} \lessgtr \mathfrak{b} > \mathfrak{a}$.

In weathered rocks the biotite is usually found to have become more or less bleached through loss of iron. These micas also become altered into chlorite or epidote, usually mixed with limonite, quartz, etc. Pseudomorphs of limonite after biotite are very common in some of the mica-porphyrites. The decomposition of the biotite frequently results in a wedging open of the crystals along the cleavage-planes. These micas are of common occurrence in a great number of eruptive rocks, both plutonic and volcanic, and also in crystalline schists. The mica-traps, minette and kersantite, in which biotite is an important constituent, occur as dykes. Biotite is often associated with muscovite, as in the granites of Cornwall and many other localities.

Rubellane is a variety of biotite of a brick-red, brownish-red, or reddish-brown colour, hematite and limonite helping to give it its rusty stain, which is not superficial, but appears as a pigment even in the thinnest scales. In convergent light, thin plates of rubellane give a dark cross which passes, on rotation of the plate, into distinct and somewhat widely separated hyperbolæ bordered by coloured fringes which faintly indicate $\rho < v$.

Anomite is a brown or reddish-brown variety of biotite, which generally differs from the other members of the series in the position of the optic-axial plane; but, although some anomite belongs to the first order of micas, it seems by no means certain, according to Rosenbusch, that there are not anomites of the second order, in which the optic-axial plane lies at right angles to the plane of symmetry. The dispersion of Tschermak's typical anomite of the first order is

$\rho > v$, while in those presumably of the second order it is $\rho < v$, as in the other biotites. The latter appear to be the anomites of most common occurrence in rocks. The pleochroism is the same as in biotite. The optic-axial angle varies from about 10° to 25°, while in the anomite of the nephelinite of Katzenbuckel $2\ E=40°$. The dispersion is always $\mathfrak{a}<\mathfrak{c}$ and $\mathfrak{b}$ with $\mathfrak{c} \gtrless \mathfrak{b}$. Anomite occurs in basalts, andesites, porphyrites, etc.

Phlogopite.—In chemical composition phlogopite is similar to biotite, the formula being $K_2 Al_2 Si_2 O_8$, with $Mg_2 Si O_4$, but with partial replacement of the first molecule by the potash-lithia-alumina molecule of lepidolite; so that, chemically, a connecting link is thus formed between phlogopite and zinnwaldite. By transmitted light, phlogopite appears colourless or of pale tints of yellow, green, or brownish yellow. The pleochroism is feeble. The absorption is $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$. In the interference-figures the separation of the hyperbolæ is slight, and the optic-axial angle is consequently not a large one, 2 E seldom exceeding 20°. The dispersion is $\rho < v$.

The phlogopites of certain localities, especially some of the American ones, show a very distinct six-rayed luminous star when a candle-flame is looked at through a thin cleavage plate of the mineral. This phenomenon, termed *asterism,* is due to the inclusions of numerous microscopic platy or flattened crystals of specular iron, often of extreme thinness, or of excessively minute crystals of tourmaline grouped in three directions which cross at 60°. The rays of this star coincide with the rays of the pressure-figure; and sometimes six other rays are developed, though in a minor degree, which correspond with the rays of the percussion-figure.

By alteration phlogopite sometimes passes into talc. It is chiefly met with in crystalline schists, especially in the beds of crystalline limestone interstratified with them.

Vermiculite and Jeffreysite are considered to be altered varieties of phlogopite.

Zinnwaldite (*Lithionite*, in part,) consists of the molecules $K_2Al_2Si_2O_8$, Mg_2SiO_4 in isomorphous admixture with the molecules $Si_{10}H_8O_{24}$, and $Si_{10}O_8Fl_{24}$ in varying proportions.

By transmitted light sections of zinnwaldite appear colourless, pinkish, or greyish-white to dark-brown. It is a mica of the second order, the optic-axial plane lying in the plane of symmetry.

The angle of the optic axes is very variable, ranging from 10° to 65°, the more ferriferous varieties having the smaller angles; in these the oblique extinction-angle is very small, but in the paler varieties the angle $c : \mathfrak{a}$ becomes considerably wider. The dispersion differs from that of all the other micas of the second order, except perhaps some varieties of anomite, in being $\rho > v$.

The pleochroism is expressed in different tints of brown in the darker varieties, while, in the paler ones, $\mathfrak{a}$ = colourless or almost so, $\mathfrak{b}$ and $\mathfrak{c}$ brownish-grey. The absorption is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$.

Zinnwaldite may be distinguished from lepidolite by the different position of the optic-axial plane with reference to the guide-line in the percussion-figure.

The presence of lithium in zinnwaldite may easily be recognised by the carmine colour which it imparts to the blowpipe-flame. It occurs chiefly in the granites of tin-bearing districts.

Muscovite (Potash Mica),—$K_2H_4Al_6Si_6O_{24}$,—occurs either in well-developed crystals or in plates and scales, the boundaries of which, except the basal planes, are irregular or jagged. By transmitted light muscovite appears colourless, or of pale yellowish or greenish tints. The colour is never sufficiently deep to give rise to any perceptible pleochroism. The absorption is, however, very strong for rays vibrating parallel to the basal planes; so that in sections at right angles or oblique to those planes a marked difference in the illumination is visible when, the analyzer being removed, the polarizer is rapidly turned. Such sections also show well-defined parallel striations, the traces of the cleavage-planes. The crystals and scales are often considerably bent. The double refraction is negative and strong. The interference-figures seen in convergent light show brilliantly-coloured rings and a wide separation of the hyperbolæ, the angle of the optic axes ranging from 40° to 70°.

The angle *c* : a made by the acute or negative bisectrix with the vertical axis, is too small to be appreciable. Thin laminæ of muscovite are flexible and elastic, laminæ of talc are flexible only. The optic-axial angle of talc is also small, while that of muscovite is very large. The two minerals may therefore be easily distinguished from one another. A very talc-like variety of muscovite, termed *sericite,* is met with in certain schists, protogine-gneiss, etc., to which it imparts a silky lustre on the planes of foliation.

Sericite occurs in extremely thin, irregularly-bounded plates or films, which, in sections transverse to their breadth, appear bent, and often contorted, their general aspect conveying the impression of a matted fibrous structure.

In optical characters sericite resembles muscovite. The blowpipe reaction with solution of cobalt nitrate affords a means of distinguishing it from talc.

Damourite is another somewhat similar variety of muscovite occurring in small scales in the staurolite-bearing schists of Brittany, and occasionally forming pseudormorphs after kyanite.

Lepidolite,—$3\ ([K, Li]_6\ Al_6\ Si_6\ O_{24}) + (Si_{10}\ O_8\ Fl_{24})$,—appears colourless, or nearly so, when viewed by transmitted light. A section normal to the basal plane, when tested by a single Nicol, shows stronger absorption for the rays vibrating parallel to the cleavage than for those vibrating parallel to the vertical axis. No pleochroism is perceptible. The angle *c* : a is inappreciable, a being apparently at right angles to the basal plane. The optic-axial angle ranges from 50° to 70° In hand-specimens lepidolite often appears of a peach-blossom red or pink colour; but this is not invariably the case, the mineral sometimes being colourless or almost so. Lepidolite can best be distinguished from muscovite by its lithium reaction. It is found principally in granite associated with muscovite.

Paragonite (Soda Mica),—$Na_2 H_4 Al_6 Si_6 O_{24}$,—occurs chiefly in certain crystalline schists, and in some cases constitutes paragonite schist. It seldom exhibits any crystallographic boundaries, except the basal planes, and usually appears in minute colourless scales, which possess the same optical properties as muscovite, and from which mineral it is only to be distinguished chemically.

Ottrelite.—$H_2 (Fe, Mn) Al_2 Si O_7$? The precise chemical composition is uncertain, owing to the difficulty of freeing the ottrelite from its inclusions.

Ottrelite occurs generally in dark greenish-grey, brownish-grey, or leek-green, irregularly-bounded crystals, or small irregular tables, which show no crystallographic boundaries, other than basal planes. Frequently the mineral assumes fusiform or lenticular shapes, often forming sheaf-like aggregates or fasciculi.

Very rarely six-sided tabular cyrstals are met with which give angles of, as nearly as possible, 120°. These crystals must be regarded as combinations of $0 P$ (001), P $(11\bar{1})$ and $\infty \breve{P} \infty$ (010). A strong vitreous lustre is seen on the basal planes, which are often curved. The faces of the prism, when present, have a resinous lustre.

Twinning upon the basal plane, similar to that met with in the micas, is almost invariably seen in sections. The cleavage is basal, but is far less perfect than that of mica. The cleavage-plates are very brittle, and are only translucent when extremely thin. Other cleavages occur, but they are either imperfect or obscure, and are associated with numerous irregular cracks. By transmitted light the mineral appears colourless, green, or blue.

The refractive index is rather high. The double-refraction is weak and positive; and sections, even when not very thin, only show, in polarized light, colours which do not rise above the first order.

In basal sections of well-developed crystals the directions of maximum extinction lie parallel and at right angles to one of the edges of the hexagon. If this edge be 001 : 010, then the axis of elasticity parallel to it will be $\mathfrak{a}$, while that normal to it will be $\mathfrak{b}$. The oblique extinction angle $c : \mathfrak{c}$ has been found to vary from 12° to 18° in sections parallel to the clinopinacoid. In such a section the direction of extinction $\mathfrak{c}$ is found to vary considerably in adjacent twin-lamellæ.

In convergent light, the acute bisectrix is found to lie obliquely (12° to 18°) to the surfaces of basal sections or cleavage-plates. In these basal sections, a single system of rings may sometimes be seen at the margin of the field, the outside of each ring being bordered with red, and the inside with blue. The dispersion is then $\rho > v$. But, as a rule, no rings are visible in these basal sections and cleavage-plates, from which it may be inferred that there is considerable variation in the angle of the optic axes. The optic-axial plane is coincident with, or parallel to, the plane of symmetry.

The pleochroism of ottrelite is very marked, $\mathfrak{a}$ = olive-green, $\mathfrak{b}$ = indigo, or plum-colour; $\mathfrak{c}$ = yellowish-green. Ottrelite may be at once distinguished from any mica by the ease with which it scratches glass, the hardness being 6 to 7.

Owing to the brittle character of the mineral, its frequent twin-lamellation, and its opacity, except in excessively thin plates, the optical investigation of ottrelite is rendered very difficult. The difficulty is also increased by the constant inclusion of tourmaline, rutile, quartz, carbonaceous matter, etc., while the presence of these substances must necessarily detract from the value of chemical analyses of ottrelite.

It occurs almost exclusively in the phyllites, or schists of very fine texture, which are mainly composed of mica, chlorite, quartz, and usually a little felspar. Ottrelite schist is a greenish-grey rock of this description, which contains plates or crystals of ottrelite, ranging from the size of an ordinary pin's head to smaller dimensions. There are several other minerals, such as masonite, chloritoid, etc., which are closely related to ottrelite, and constitute a group known as the ottrelite, or chloritoid group.

Monoclinic Felspar Group.

The monoclinic felspars are Orthoclase and its varieties, Adularia and Sanidine, with some others of less importance. **Orthoclase** occurs in many plutonic rocks and their apophyses, in crystalline schists, in a fragmental condition in arkose, and, subordinately, in various sandstones and grits. Adularia, a transparent variety, is met with in the gneiss, chlorite schists, etc., of certain localities, notably St. Gothard, while sanidine, or glassy felspar, is essentially a constituent of volcanic rocks.

The chemical composition of these felspars is represented by the formula $K_2 Al_2 Si_6 O_{16}$. Orthoclase occurs in porphyritic rocks in well-developed crystals. In crystalline-granular rocks, however, the mineral is generally in a less perfectly-developed condition, conforming more or less to the boundaries of the crystals by which it is surrounded, while in the crystalline schists, gneiss, etc., orthoclase frequently exhibits no crystallographic form, occurring in irregular grains which often seem compressed, or elongated into fusiform or lenticular shapes.

The crystals usually show the following combinations: $\infty \not{P} \infty$ (010), ∞P (110), P ($\bar{1}11$), $\bar{P} \infty$ ($\bar{1}01$), $2 \not{P} \infty$ (021), 2 Ᵽ ∞ (2̄01), and 0 P (001). Other faces are sometimes developed, but they are less common.

The angle of the prism (110) is 118° 48′; the angle of the basal plane (001) to the hemiorthodome (1̄01) is 129° 40′; that of (001) to (2̄01) = 99° 37′; (110) to (010) = 119° 36′, and (001) to (010) = 90°.

The crystals vary in habit, the great development of the clinopinacoids in some, rendering them more or less tabular, while in others, the extension of the basal planes and clinopinacoids in the direction of the clinodiagonal axis causes them to assume a prismatic habit, which is well shown in the crystals from Baveno, in Italy.

Orthoclase crystals are frequently twinned. The most common kind of twinning is that known as the *Carlsbad type*, in which the twinning plane is parallel to the orthopinacoid ∞ Ᵽ ∞ (100), while the plane of composition is the plane of symmetry, the axis of twinning being normal to the orthopinacoid. Sometimes the two halves of the twin partially penetrate, and the twinned crystals may be distinguished as right- and left- handed, according to whether the reversed half lies to the right or left of the observer.

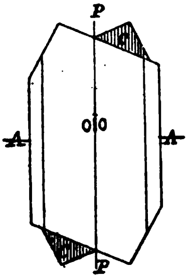

Fig. 102.

Fig. 102 represents a right-handed Carlsbad twin of orthoclase, in which PP is the trace of the twinning plane, CC the plane of composition, and AA the twin axis.

Another type of twinning, less common, however, than the Carlsbad, is the Baveno type. In this the twinning-plane is parallel to the clinodome 2 P̄ ∞ (021), and it is also the plane of composition. The twinning axis is, of course, normal to the twinning plane. In this type, the basal plane pertaining to one half of the twin is brought to a position at right angles to the basal plane of the other half. The Baveno type is only met with in those crystals of orthoclase which have a prismatic habit in the direction of the clinodiagonal axis. A section through such a crystal, parallel to the orthopinacoid, is approximately square.

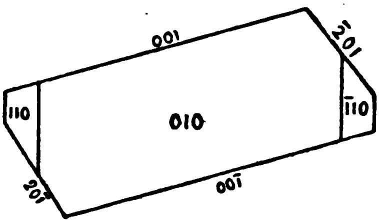

Fig. 103.

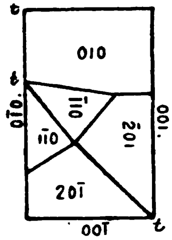

Fig. 104.

Fig. 103 is an elevation of the untwinned crystal on the plane of 010, while Fig. 104 represents such a crystal twinned on the Baveno type, the trace of the twinning plane being indicated by the line *t t t t*. It will also be noted in this figure that 001 is brought to a position at right angles to 001̄.

A third and still less common type of twinning, is the Manebach type, which is occasionally met with in the felspars of quartz-porphyries. In this case, the plane of twinning, also the plane of composition, is parallel to the base, the twin axis being normal to 0 P (001).

The two principal directions of cleavage in orthoclase are parallel to 0 P (001), and to ∞ P̄ ∞ (010). Of these, the former is rather the better and easier. They intersect at right angles.

Sections of orthoclase appear colourless by transmitted light. The refractive index is nearly that of Canada-balsam, $\alpha=1{\cdot}5190$, $\beta=1{\cdot}5237$, $\gamma=1{\cdot}5260$ for yellow light.

The double refraction is always negative and weak. The colours in polarized light are not higher than the first order.

The optic-axial plane is generally at right angles to the plane of symmetry, and the acute bisectrix $\mathfrak{a}$ usually makes an angle of from 3° to 7°, with the clinodiagonal axis, *a*; in some instances, however, it has been found to reach 12°. Owing to the inclination of the acute bisectrix, and, of course, of the optic-axial plane with it, the optic normal $\mathfrak{b}$ also makes a proportionate angle with the vertical axis. Orthoclase, in which the optic-axial plane has this position, is designated by Fouqué and Lévy, *orthose non-déformé*, or normal orthoclase. Fig. 108. In normal orthoclase, the dispersion is horizontal, and always $\rho > v$. The directions of extinction in all sections in the orthodiagonal zone are parallel, and at right angles to the directions of the basal and clinopinacoidal cleavages.

In sections parallel to the clinopinacoid, the oblique extinction angle is about 21°. In other sections in the zone (010 : 100), the extinction-angle increases very gradually until the sections have an inclination of more than 45° to the clinopinacoid, 010, when the angle augments rapidly, attaining 90° when the section is parallel to the orthopinacoid 100. The traces of the optic-axial planes in Carlsbad twins are parallel, as may be seen by examining an orthopinacoidal section in convergent polarized light. This, or a basal section, will also show simultaneous extinction when parallel polarized light is employed, the basal and clinopinacoidal cleavage planes lying respectively parallel to the two directions of maximum extinction. In the zone $\infty\bar{P}\infty$ (100) : $\infty\breve{P}\infty$ (010), both the cleavage planes and the directions of maximum extinction in sections parallel to the orthopinacoid are parallel and at right angles to the plane of composition.

In sections parallel to the clinopinacoid, only the cleavage planes parallel to the base (001) are seen. Such sections, if not absolutely, but nearly, parallel to the symmetral plane, as in Fig. 105,—(where *s s* = the plane of section, *c c* = the plane of composition or of symmetry, $\mathfrak{b}$ = the optic normal in the right half, and $\mathfrak{b}'$ that in the left half of the twin,)—show the basal cleavage planes inclined in opposite directions, and meeting, where the section crosses the plane of composition, in an angle of about 127°; and, as the angle $c:\mathfrak{b}$, made by the optic-normal with the vertical axis is about 21°, in sections parallel

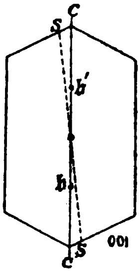

FIG. 105.

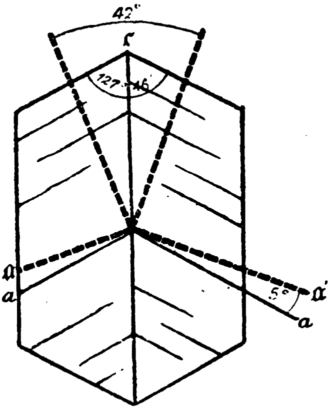

FIG. 106.

to the clinopinacoid, so, in such an almost coincident section, the angle $c:\mathfrak{b}$, in the two halves of the twin, make together an angle of about 42°, as shown in Fig. 106, where cc = the trace of the plane of composition, through which the section is supposed to pass obliquely at a very small angle; xx = the basal cleavages, $\mathfrak{b}\mathfrak{b}'$ = the optic normals, and $\mathfrak{a}\mathfrak{a}'$ = the acute bisectrices. In other sections in the same zone (100 : 010), the angle formed by the directions of extinction $\mathfrak{b}$ and $\mathfrak{b}'$ increases in proportion to the inclination of the section to the clinopinacoid (010), the increase of the angle from 42° being at first slow, but in sections of more considerable inclination to (010) the angle increases rapidly towards 180°. Under similar conditions, the angle formed by the basal cleavage planes in the two halves of the twin also increases from 127° 46′ to 180°. The plane of composition always halves the cleavage planes and extinction angle symmetrically in sections in the zone (100 : 010). The zone (001 : 010), however, in one-half of a Carlsbad twin, approximates to the zone of Ꝑ∞ ($\bar{1}01$) in the other half. In the first individual or half of the twin, we then find that the cleavage planes lie parallel to the plane of composition, and that the direction of extinction makes an angle with the plane of composition which increases from 0° in basal sections to 12° in sections nearly parallel to the clinopinacoid. In the second half of the twin, the cleavages intersect at right angles, and the extinctions are respectively parallel to the two directions of cleavage.

In this zone (001 : 010) the angle made by the cleavages increases as the direction of the section approaches the clinopinacoid (010), reaching eventually 54°, while the angle made by the direction of extinction with the plane of composition also increases from 0° to 47°.

In othoclase crystals twinned on the Baveno type, sections parallel or approximately parallel to the orthopinacoid show rectangularly intersecting cleavages, traversed diagonally by the trace of the plane of composition, which is also the twinning-plane. The trace of this plane also runs diagonally to the boundaries of such a section, which, owing to the prevalent habit of the Baveno crystals, is approximately square.

A section of this kind, when examined in convergent polarized light, shows a different position of the optic-axial plane on either side of the twinning plane, the interference-figure in one half of the twin having the optic-axial plane parallel to one of the edges of the section, while that in the other half has its optic-axial plane lying in a direction at right angles to that of the first interference-figure, as indicated in Fig. 107.

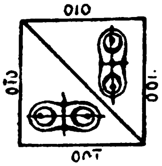

Fig. 107.

In the crystals already described, the optic-axial plane was seen to be situated at right angles to the plane of symmetry, and such crystals were termed normal orthoclase. Sometimes, however, orthoclase crystals are met with in which the optic-axial plane lies *in* the plane of symmetry, and these may be termed abnormal orthoclase (*orthose déformé* of Fouqué and Lévy). Fig. 109.

Crystals of this kind are not common, and they are chiefly found in volcanic ejectamenta, less frequently in lavas. Such crystals show an *inclined* dispersion, which is always $\rho < v$. The acute bisectrix, as in the normal orthoclase, is the axis of greatest elasticity, $\mathfrak{a}$, and it makes an angle of about 5° with the clinodiagonal. The axis of least elasticity, $\mathfrak{c}$, which is also the obtuse bisectrix, makes an angle of 21° 7′ with the vertical axis c. The angle of the optic axes is small, and sometimes too small to be measurable, 2 E=40° to 0°. The limit of 2 V=64°, while in the normal orthoclase the limit of 2 V=69°.

Crystals of abnormal orthoclase have either been formed at a high temperature, or have been heated subsequently to their formation.

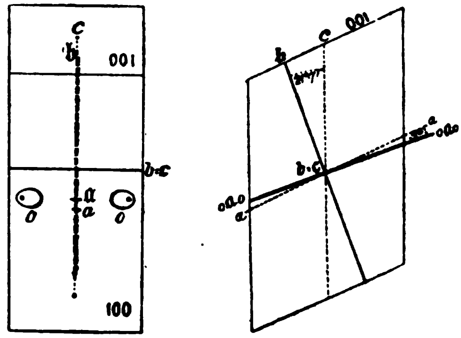

FIG. 108. (*Normal Orthoclase.*)

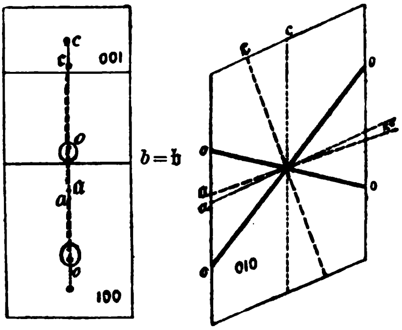

FIG. 109. (*Abnormal Orthoclase.*)

When crystals of orthoclase are artificially heated, the position of the optic-axial plane changes; and if raised to a temperature over 500° C., the optic axes do not absolutely revert to their normal positions; while if raised from 600° to 1000° C., their altered position becomes permanent.

Instances are sometimes met with in which the optic-axial plane for blue light lies parallel to the clinopinacoid (010), while for red light it is normal to (010), a phenomenon somewhat analogous to that seen in the rhombic system in brookite, except that in the latter case there is a common bisectrix for light of all colours.

The optical characters of orthoclase vary considerably, the variation being apparently due, in part, to substitution of sodium for potassium, and also to conditions of unequal tension within the crystals. Pleochroism is not seen in orthoclase, nor is there any very perceptible difference of absorption.

The relative positions of the optic axes, bisectrices, etc., in normal and abnormal crystals of orthoclase, have already been shown in Figs. 108 and 109.

Intergrowths of triclinic felspar with sanidine are of frequent occurrence. In such cases the clinopinacoids of the sanidine and the brachypinacoids of the triclinic felspar are parallel to one another.

In phonolites the sanidine sometimes becomes converted into zeolitic matter. Sanidine crystals also frequently show cleavage or separation-planes parallel to the orthopinacoid.

The crystals of sanidine are of a tabular habit, owing to the great development of the clinopinacoids; but a similar habit is also prevalent in common orthoclase. Adularia represents a very pure orthoclase. Intergrowths of microline albite and oligoclase frequently occur in orthoclase.

Epidote.—Under this name are included several varieties, which differ more or less in their chemical composition. According to Tschermak, epidote may be regarded as a mixture of two silicates, namely—

$$H_2\ Ca_4\ Al_6\ Si_6\ O_{26} \text{ (or Zoisite silicate)}$$

$$\text{with } H_2\ Ca_4\ Fe_6\ Si_6\ O_{26} \text{ (or Epidote silicate).}$$

Of these two silicates, the former (which crystallizes, as zoisite, in the rhombic system) is dimorphous. In the epidotes, mixture of the epidote- with the zoisite- silicate occurs in various proportions, the ferrous oxide attaining 17 per cent. in some instances. Those varieties which contain the lowest percentage of iron constitute the *lime-alumina epidotes* which have the same composition as zoisite. The more ferriferous varieties constitute *epidote proper*, in which a considerable amount of alumina is often replaced by ferric oxide, while a similar replacement of alumina by manganic oxide results in Piedmontite or manganese-epidote. Epidote usually occurs, in rocks, in irregularly-shaped crystalline grains or aggregates of minute, rod-like crystals, which, like the larger crystals, have a long prismatic habit by extension in the direction of the orthodiagonal axis *b*.

Considerably larger and well-developed crystals are, however, occasionally present in rocks, and are usually combinations of the basal plane 0 P (001), the orthopinacoid $\infty \bar{P} \infty$ (100) and the orthodome $\bar{P} \infty$ ($\bar{1}01$), all of which faces lie in the orthodiagonal zone, the longitudinal prism thus formed being closed, in perfectly-developed crystals, by faces of prisms or pyramids, as in Fig. 110. A section of such a crystal, taken parallel to the plane of symmetry, which here would be at right angles to the plane of the paper on which Fig. 110 is printed, would be a somewhat irregular hexagon; while similar sections of crystals in which the orthopinacoids were absent, as is frequently the case, would be rhombs.

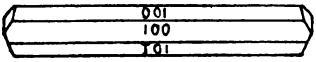

FIG. 110.

Sections parallel to the orthodiagonal or *b* axis would have a long, narrow, lath-like shape, the breadth, of course, depending upon the direction, in the orthodiagonal zone, in which the face was cut, or on the distance of the section from a crystallographic edge. The cleavage is perfect parallel to the basal plane, less perfect parallel to the orthopinacoid. The two directions of cleavage intersect at 115° 24′ in sections parallel to the clinopinacoid.

Epidote, as it appears in thin sections of rocks, is either colourless or of a clear yellow, green (especially yellowish-green), or yellowish-brown tint, seldom red.

The refractive index is high and the double refraction negative and very strong. Irregularities on the surfaces of slices consequently appear well marked, and the borders of crystals are also strongly defined through total reflection. The colours in polarized light are brilliant, and especially so in slices parallel to the plane of symmetry, in which even thin sections exhibit colours of the third order—a range of colour which, as pointed out by Rosenbusch, is equalled by few other silicates, and is only surpassed in sections of rutile, anatase, zircon, and the rhombohedral carbonates. In the well-known crystals of the Untersulzbachthal, the refractive indices have been determined as $\alpha=1{\cdot}730$, $\beta=1{\cdot}754$, $\gamma=1{\cdot}768$ for red light.

The optic-axial plane in epidote lies in the plane of symmetry. The acute (negative) bisectrix, 𝔞, or axis of greatest elasticity, lies in the acute angle formed by the clinodiagonal and the vertical axis, and makes an angle with the latter of about 2° to 3°, as shown in Fig. 111. In convergent light, all sections cut in the orthodiagonal zone show interference-

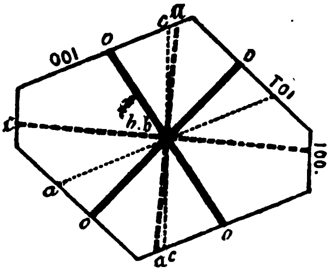

Fig. 111.

figures, or the dark bars, one corresponding with the optic normal and the other with a bisectrix. In these sections the bar corresponding with the optic normal lies parallel to the traces of the cleavage planes, whether basal or orthopinacoidal; and consequently the bisectrix (therefore also the optic-axial plane) lies at right angles to the cleavage.

Sections in the orthodiagonal zone also have their directions of maximum extinction parallel and at right angles to the cleavage; and there is, therefore, risk of mistaking such sections for those of a rhombic mineral.

In sections in the zone (100 : 010) the extinction angles range from 0° in sections parallel to (100) to about 28° in those parallel to (010); while the same range of extinction angles is met with in sections in the zone (001 : 010), the highest angle, about 28°, occurring in the clinopinacoidal section.

Pleochroism, although excessively strong in the dark-coloured transparent crystals of epidote, such as are seen in mineralogical collections, is much less marked in their rock-forming representatives, being generally $\mathfrak{a}$=colourless or pale yellowish-green, $\mathfrak{b}$ = colourless or yellowish-green, $\mathfrak{c}$ = siskin-green or yellowish-brown.

The absorption in these rock-forming epidotes is $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$, while in the large dark epidote crystals from Knappenwand it is $\mathfrak{b}>\mathfrak{c}>\mathfrak{a}$; and in the Japanese crystals of piedmontite or manganese epidote described by Kotô, the absorption is $\mathfrak{a}>\mathfrak{c}>\mathfrak{b}$, where $\mathfrak{a}$=deep reddish-violet, $\mathfrak{c}$ = brownish, red, $\mathfrak{b}$ = light violet.*

Twinning, although common enough in the larger crystals is less frequently seen in the epidote occurring in rocks. The

* Piedmontite occurs in the mica schists of the Ile de Groix, off the south coast of Brittany ("Bull. Soc. Fran. de Min." t. xi. p. 148); and it has recently been met with in one or two British localities. This species must, therefore, now be included among well-recognised rock-forming minerals.

twinning plane is parallel to the orthopinacoid, and it is also the plane of composition. Thin twin lamellæ sometimes lie between the larger portions of a twin crystal.

Epidote is never a normal constituent of eruptive rocks, although it is of very frequent occurrence in them as a decomposition product. It is an important factor in many crystalline schists and gneisses and is often met with in metamorphosed limestones.

Wherever the needful elements are present in a rock-forming silicate, as in the pyroxenes, amphiboles, etc., decomposition is almost certain to give rise to more or less epidote.

Orthite (Allanite) is isomorphous with epidote; and its chemical composition may be regarded as that of an epidote in which the lime is partly replaced by the oxides of cerium, lanthanum, didymium, and yttrium, while perhaps sesquioxides of these metals are also substituted for some of the alumina, and basic water may likewise be present. In form, cleavage and optical characters, it resembles epidote. Sections of orthite, seen by transmitted light, are of a reddish-brown or greenish-brown colour. Rosenbusch states that they frequently appear isotropic, although no signs of decomposition are perceptible.

The optic-axial plane is the plane of symmetry, as in epidote. In specimens examined by Iddings and Whitman Cross, it was found that one of the bisectrices made an angle of 35° to 40° with the vertical axis, and 25° to 30° with the clinodiagonal. These authors show that the mineral has a very wide distribution in the United States, although often it only occurs in a rock in very small quantity. They record its occurrence in rhyolites, dacites, and andesites, diorites, granites, gneiss, etc. According to G. vom Rath, it is met with in considerable quantity in tonalite, a rock allied to quartz-diorite. Its occurrence in the granitic and gneissic rocks of Scandinavia, Greenland, etc., has long been known.

Sphene (Titanite).—CaO, SiO_2, TiO_2, or $\left\{\begin{matrix} Ca & Si_2 & O_5 \\ Ca & Ti_2 & O_5 \end{matrix}\right\}$ The dark varieties generally contain ferrous oxide up to about five per cent.

As a normal, but subordinate, constituent of eruptive rocks, sphene always occurs in well-developed, although usually small, crystals, which vary considerably in their forms. Of these, the most common consists of a combination of $\frac{2}{3}$ Ᵽ 2 ($\bar{1}23$), 0 P (001) and Ᵽ ∞ ($\bar{1}01$), as in Fig. 112.

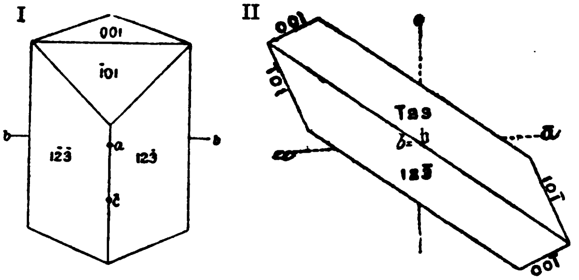

FIG. 112.

Another combination especially common in schistose rocks is $\frac{2}{3}$ Ᵽ 2 ($\bar{1}23$) and ∞ P (110). Fig. 113 represents this extremely sphenoidal sphene.

Figs. 112, I. and 113, I. show the crystals in the position in which they should be read. They are projections on the plane

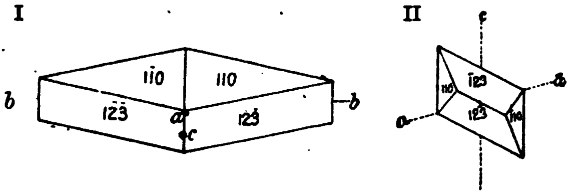

FIG. 113.

(100), and in both figures the faces of $\frac{2}{3}$ Ᵽ 2 ($\bar{1}23$) are greatly fore-shortened, their inclination to the plane of projection being shown in Figs. 112, II. and 113, II. Here, to facilitate the student's recognition of the relation of Naumann's hemipyramids to the other forms which enter into the combination, the positions of crystallographic axes are indicated. In Fig. 113, the angle $\infty P : \infty P = 133° 52'$, while $\frac{2}{3} \bar{P} 2 : \frac{2}{3} \bar{P} 2 = 136° 12'$.

Sections showing twinning on a plane parallel to the orthopinacoid, as in Fig. 114, are very characteristic of sphene.

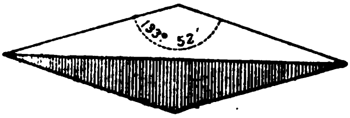

Fig. 114.

Twinning upon the basal plane is also common. The cleavage is parallel to (110), but, owing to the frequent absence of these faces, and the prevalence of those of $\frac{2}{3} \bar{P} 2$ $(\bar{1}23)$, it is a very usual thing to find the cleavage cracks abutting obliquely against the boundaries of sections formed by the latter faces.

Moderate-sized crystals of sphene generally present greenish-yellow, green, or brown colours; but the small crystals occurring in rocks are usually colourless, or of pale yellowish or reddish tints, they are, however, sometimes of a deep reddish-brown, and, in the latter case, they are not very translucent. Dark borders, seen by substage illumination, indicate the very high refractive index of the mineral, and the consequent total reflection on the margins of sections, the surfaces of which also show any roughness or irregularity in a very marked manner. The double refraction is positive and not particularly strong, but the dispersion $\rho > v$ is so, as shown by the lines $\rho\ \rho$ and $v\ v$ in Fig. 115.

The optic-axial plane is in the plane of symmetry; and, when the form $\frac{1}{2} \bar{P} \infty$ $(\bar{1}02)$ is present, the acute bisectrix is seen to be normal to that face, while the obtuse bisectrix, or axis of least elasticity, $\mathfrak{c}$, makes an angle of 39° 17′ with the vertical crystallographic axis *c*, or with the edge (100 : 010). The acute bisectrix lies in the obtuse angle β. There is but

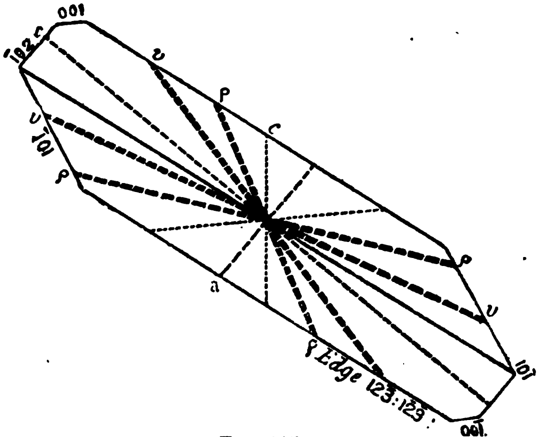

FIG. 115.

very slight dispersion of the bisectrices for different coloured light; but the dispersion of the optic axes is considerable, as may be seen in the interference-figures by placing a red, and afterwards a blue, glass beneath the stage of the instrument. According to Des Cloizeaux, the apparent angle for red light $2\ E\rho = 56°$ in one instance, while for blue $2\ E\upsilon = 34°$. These are, however, the highest recorded measurements.

In convergent polarized light, sections in the orthodiagonal zone give interference-figures, or else the cross corresponding to a bisectrix and the optic normal. The pleochroism is barely perceptible, except in deeply coloured sections, where 𝔞=approximately colourless, 𝔟=greenish-yellow, 𝔠=yellowish-red.

Sphene, when it occurs as a normal constituent of eruptive rocks, must be regarded as one of the first minerals which crystallized out from the magma. It is found in granites, syenites, especially the elæolite-syenites, diorites, trachytes, etc., and often rather plentifully in gneiss and crystalline schists. Sphene sometimes becomes altered into rutile, at others into a whitish substance, the precise nature of which has not yet been determined.

Gypsum,—$CaSO_4+2H_2O$,—is chiefly, if not exclusively, met with in sedimentary rocks, and, as a rock constituent, occurs in irregularly-bounded crystalline grains. When filling small veins, it frequently assumes a fibrous character (satinspar, in part).

Gypsum, in thin sections or thick, is usually colourless, but intensely-red gypsum is sometimes found, the colour being due to admixture with ferric oxide. The double-refraction is negative and remarkably strong. By examining crystals (selenite), the optic axes are found to lie in the symmetral plane; and the interference-figure, in convergent light, shows inclined dispersion. The angle of the optic axes is 2 V. 61° 24′ at the ordinary temperature. The change produced in the optic-axial angle and in the optic-axial plane on the application of heat, is one of the most beautiful phenomena to be seen in the polariscope. The acute bisectrix $\mathfrak{a}$ lies in the obtuse angle β. The angle of oblique extinction $c : \mathfrak{a} = 75° \; 15'$. Selenite has a highly-perfect cleavage parallel to the clinopinacoid.

Twinning on the orthopinacoid is common, the twinning-plane being also the plane of composition. There is another type of twinning, in which the twin axis is a normal to $- \bar{P} \infty$ (101). The percussion-figure produced in cleavage plates of selenite is a cross, the arms of which intersect at about 60°.

TRICLINIC SYSTEM.

Triclinic crystals, as already mentioned, are symmetrical only to a central point; and no form in this system consists of more than a single pair of faces. Sections taken in any zone are consequently indivisible symmetrically by any line.

The crystals of this system never possess two similar directions of cleavage. No relation exists between any of the axes of elasticity and the crystallographic axes; but occasionally an axis of elasticity will be found to approximately coincide with a crystallographic axis, and the optical character of such a crystal will then resemble that of one belonging to the monoclinic system. The directions of maximum extinction are usually seen to lie obliquely to the boundaries of sections and to cleavage-planes. Sometimes two or more kinds of dispersion are to be seen in sections of triclinic crystals, when they are examined in convergent light. The distribution of the colours in the interference-figures is unsymmetrical.

All sections of triclinic crystals, when not at right angles to an optic axis, exhibit pleochroism, assuming, of course, that the crystal possesses colour.

Microcline.—Chemical composition the same as that of orthoclase. Although microcline crystallizes in the triclinic system, the general habit and the angles of the crystals approximate very closely to those of orthoclase. The cleavages parallel to the basal plane and the clinopinacoid in orthoclase intersect at 90°, while in microcline the corresponding basal and brachypinacoidal cleavages make an angle which only differs from 90° by less than a quarter of a degree; and there is an equally close approximation in the angle formed by the corresponding faces in crystals of these two minerals.

Crystals of microcline occur in cavities and fissures in certain granitic rocks, and very closely resemble those of orthoclase in external form—so closely, in fact, that it is difficult to appreciate any difference in this respect. These microcline crystals, however, differ in internal structure from crystals of orthoclase, inasmuch as they have a composite or polysynthetic structure, due to the development of minute twin lamellæ. The twinning is upon two different types, respectively known as the *albite-* and *pericline- types.* The two systems of twin lamellæ give a peculiar cross-hatched appearance to sections, when viewed in parallel polarized light, an appearance so peculiar that the student, having once seen it, will have little difficulty in recognising it again. In addition to this lamellation, microcline frequently shows irregular intergrowths of albite, and also of orthoclase. The twin lamellæ which follow the pericline type, lie in the direction of the basal plane, and produce a delicate banding parallel to the edge (001 : 010) in sections parallel to (010); while, in those parallel to (100), the fine bands lie parallel to the edge (001 : 100).

On the other hand, those twin lamellæ which conform to the albite type, lie parallel to the brachypinacoid $\infty \breve{P} \infty$ (010), and parallel to the edge (001 : 010) in basal sections; while in sections parallel to the orthopinacoid (100) they run parallel to the edge (100 : 010).

Since, in microcline, the basal- and brachy- pinacoids form an angle which deviates from a right angle by a few minutes only, these lamellæ, resulting from twinning on the pericline and albite types, form, by their intersection, an angle which deviates so slightly from 90° that, to all appearance, they cross at right angles in sections in the macrodiagonal zone. In some instances, as in the large green crystals from Pike's Peak in Colorado, the cross-hatching due to this structure can often be seen upon the basal plane without employing even a pocket lens. These larger crystals appear also to twin on a larger scale upon the Carlsbad type, quite independently of the Baveno and Carlsbad types of, what one may term, microscopic twinning.

In addition to the basal- and brachy- pinacoidal cleavages,—which so closely approximate to the corresponding cleavages in orthoclase that practically no distinction need be made between them,—there is a hemiprismatic cleavage in microcline, parallel to $\infty\,'P$ (110), but it is not a very distinct one.

In thin sections, microcline appears colourless by transmitted light. The optic-axial plane in microcline does not lie quite at right angles to the brachypinacoid, as it does to the clinopinacoid in orthoclase, but makes with (010) an angle of 82° to 83°. The obtuse bisectrix c does not lie at right angles to (010) as in orthoclase, but makes an angle of between 15° and 16° with a normal to that face.

The optic-axial angle in oil, Ha = 88° to 90°—Fig. 116, shows the position of the bisectrices in a cleavage plate parallel to the basal plane, the acute edge (001 : 010), from which the extinction-angles are measured, being represented by the line E E on the right of the figure. The acute bisectrix is a; the

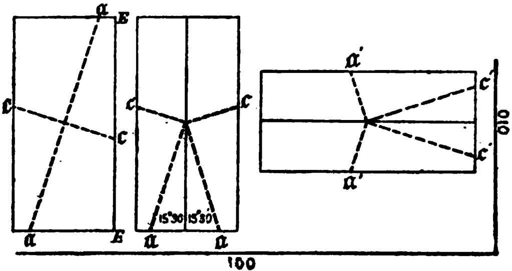

Fig. 116. Fig. 117. Fig. 118.

obtuse, c. The former makes an angle of 15° 30′ with the edge E E. This oblique extinction-angle in basal sections affords an important means of identifying microcline. In Fig. 117 a crystal giving a basal section like that in Fig. 116 is assumed to be twinned on the albite type, *i.e.*, on a plane parallel to (010), the right half being inverted. In a basal section of this description the directions of extinction are exactly reversed on opposite sides of the twinning plane, which, in this case, is also the plane of composition. Assuming the section to stand as it is represented, with the principal sections of the crossed Nicols parallel and at right angles to the plane of composition, or line dividing the section vertically, it would be necessary to turn the section 15° 30′ to the left in order to get maximum extinction in the left half; while to cause similar extinction in the right half, a rotation of 15° 30′ to the right would be needed. The two directions of extinction in such a section make, therefore, an angle of 31° with one another.

As already stated, crystals of microcline are seen in parallel polarized light to be composed of a vast number of minute twin lamellæ which intersect at right angles, or at an angle which deviates inappreciably from 90°. The twin lamellæ lying in one of these directions follow the albite type of twinning, while those at right angles to them are twinned on the pericline type; and these latter lamellæ lie parallel to the edge (001 : 100) or $(0\,P : \infty \bar{P} \infty)$. The relation of the lamellæ twinned on the albite and pericline types is indicated in Figs. 117 and 118 respectively, by the lines ruled beneath and to the right of them, these lines denoting the traces of the macropinacoid 100, and the brachypinacoid 010. When two such lamellæ cross, as they do in a crystal of microcline, at 90°, the directions of maximum extinction in the one lamella coincide with, or are parallel to, those in the other, as indicated by the thick lines in Fig. 119, which constitute a double set of rectangular directions of extinction deviating from one another by 31°, 𝔞 𝔞′ *o*, 𝔠 *o* 𝔠′ representing one set of extinctions, and 𝔞 *o* 𝔞′, 𝔠′ 𝔠 *o* representing the other.

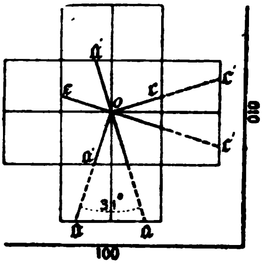

FIG. 119.

In consequence of this, basal sections of microcline, when rotated 15° to 16° from the position in which the two directions of the twin lamellæ are parallel to the principal sections of the crossed Nicols, show simultaneous extinction in both sets of lamellæ. Intergrowths of albite and orthoclase are frequently to be seen in such sections, when the latter mineral may be recognised by its parallel, or straight, extinction. The albite has an extinction-angle of between 4° and 5° in basal sections. In sections of microcline parallel to the brachypinacoid, the trace of the optic-axial plane makes an angle of 5° to 6° with the edge (001 : 010) or $(0\ P : \infty\ \breve{P}\ \infty)$, and also with the traces of the cleavage planes parallel to the base. If, therefore, in such a section the cleavage cracks lie parallel to the principal section of one of the crossed Nicols, a rotation of the section through 5° or 6° will produce the maximum extinction. The axis of greatest elasticity $\mathfrak{a}$ is seen in sections of microcline parallel to 010, to be inclined to the crystallographic axes, or their corresponding edges, in such a manner that on the face 100 it emerges above, and on $\bar{1}00$ below, the clino-diagonal axis, making with the latter an angle of 5°.

In convergent light, sections parallel to (010) show part of a system of rings about one of the optic axes, but the axis emerges obliquely outside the field. The alterations which microcline undergoes are similar to those which orthoclase experiences; and the two minerals very often occur together in the same rocks.

Plagioclastic Felspar Group.

The other Triclinic felspars are grouped together under the common denomination of plagioclase, and, as rock-forming minerals, they are of great importance.

According to the theory enunciated by Tschermak, and now generally accepted, they constitute a series of which albite and anorthite are the extremes, while the other members of the series are regarded as isomorphous mixtures of these two types in various proportions.

The molecular relations, with the limits of variation in the different species, are shown in the following table, where Ab denotes the albite, and An the anorthite molecule :—

Albite	Series . . .	$Ab_1\,An_0$ —— $Ab_8\,An_1$
Oligoclase	„ . . .	$Ab_6\,An_1$ —— $Ab_2\,An_1$
Andesine	„ . . .	$Ab_3\,An_2$ —— $Ab_4\,An_3$
Labradorite	„ . . .	$Ab_1\,An_1$ —— $Ab_1\,An_2$
Bytownite	„ . . .	$Ab_1\,An_3$ —— $Ab_1\,An_6$
Anorthite	„ . . .	$Ab_1\,An_8$ —— $Ab_0\,An_1$

in which $Ab = Na_2\,Al_2\,Si_6\,O_{16}$, and anorthite $= Ca_2\,Al_4\,Si_4\,O_{16}$.

Crystals of plagioclastic felspar are very like those of microcline; but they differ from them in the fact that the angle made by their basal and brachy pinacoids deviates several degrees from a right angle, in some cases over 4°. In albite the angle 001 : 010 = 93° 36′, while in anorthite it is 94° 10′. In microcline this angle does not exceed 90° 25′. The other angles of the plagioclastic felspar crystals also differ more or less from the corresponding angles in microcline. Occasionally the crystals are combinations of the forms $\infty{}',P = (1\bar{1}0)$, $\infty P',$ $= (110)$ and $2,\bar{P},\infty = (\bar{2}01)$, all pinacoidal faces, including the basal pinacoids, being absent, as in Fig. 120, in which case

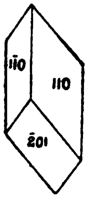

FIG. 120.

the general aspect of the crystal is that of a rhombohedron. The crystals are very commonly tabular through the predominance of the brachypinacoids, as in Fig. 124; while, at times, extension in the direction of the axis *a* gives rise to a long-prismatic habit.

Twinning is so common in the plagioclastic felspars that it is the exception to find an untwinned crystal. A simple twin composed of only two halves or individuals, as in Fig. 121, is also of comparatively rare occurrence, the twinning being usually many times repeated; so that a crystal of plagioclastic felspar is, as a rule, composed of a great number of parallel twin-lamellæ. It is now ascertained that this often-repeated twin-lamellation may be developed artificially in untwinned felspars, a high temperature having been found in some cases, as in Förstner's experiments, sufficient to bring about this molecular change, while, in other instances, it may have been superinduced by pressure, as in Reusch's experiment with calcite. The most common type of twinning in the triclinic felspars is the albite type, in which the twin-axis is a normal to the brachypinacoid $\infty \breve{P} \infty$ (010). By this method of twinning the basal planes of adjacent individuals, or lamellæ, make a re-entering angle of 172° 48′, while their macrodomes $,\bar{P},\infty$ ($\bar{1}01$) also form a re-entering angle of 172° 42′, Fig. 121. A basal section of such a crystal may be distinguished from a similar section of orthoclase, twinned on the Carlsbad type, by the directions of maximum extinction in parallel polarized light not being parallel, or at right angles, to the edges (001 : 100) and (100 : 010), while the basal section of orthoclase would give parallel or straight extinctions. In the most common

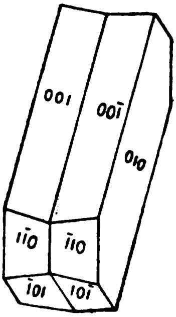

Fig. 121.

crystals of plagioclastic felspar the repetition of the twinning on the albite type results in a series of delicate ridges and furrows which are perceptible as fine striæ on the basal planes, the striation being parallel to the edge (001 : 010).

A section of such a crystal parallel to the macropinacoid

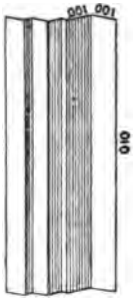

Fig. 122.

would, therefore, appear as in Fig. 122, where the shaded bands represent the reversed lamellæ, while the serrated edges are the traces of the basal planes, alternately reversed.

In parallel polarized light such sections show parallel bands of different colours. These are not always continuous throughout the entire length of the section, but frequently end abruptly; at other times they appear to thin out. The pressures to which these crystals have sometimes been subjected, and the consequent flexure which they occasionally display, seem to have a marked influence upon the distribution and continuity of these twin lamellæ.

The pericline type of twinning, first explained by G. vom Rath (Neues Jahrbuch, 1876, p. 689), and so named from pericline, a variety of albite, is far less common in plagioclastic felspars than the albite type. In the pericline type the twin-axis coincides with the crystallographic axis *b*, and the plane of composition or contact is the so-called *rhombic section*; *i.e.*, a plane which passes through the rhomboidal prism so that the angle which it forms on the faces, $\infty P'$ and $\infty \bar{P} \infty$ on the one hand and that on $\infty\, 'P$ and $\infty \breve{P} \infty$ on the other are equal.

In sections showing this type of twinning, the traces of the planes of compositionare either parallel to or oblique to the trace of the basal plane; and, in sections parallel to the brachypinacoid, the twin lamellæ are seen to lie in the manner and approximately at the angles shown in Fig. 123. Here, in andesine, the lamellæ are seen to run parallel to the edge $(0P : \infty \breve{P} \infty) = (001 : 010)$. In albite the inclination is 13° to 22° to this edge. In oligoclase it is only 4°, the lamellæ in both of these felspars being less inclined than the edge (001 : 010). In labradorite and anorthite, however, the inclination of the lamellæ is greater than that of the edge (001 : 010), the angle in labradorite being 2° to 9°, while in anorthite it is 18°.

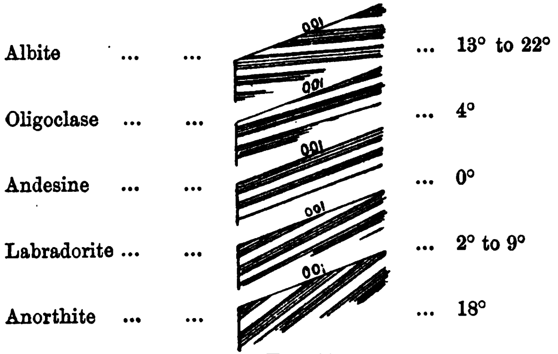

FIG. 123.

Sometimes both the albite and pericline types of twinning are met with in the same crystal, the two sets of lamellæ intersecting nearly at right angles upon the basal plane and the macropinacoid, while upon the brachypinacoid the twinning upon the pericline type is shown by the lamellæ lying parallel to the rhombic section of the prism, and in the positions indicated in Fig. 123, where the varying inclination of the rhombic section to the edge 001 : 010 in the different species is shown. In crystals in which both of these types of twinning exist, a *simple* twin-lamellation is only to be seen in sections parallel to the brachypinacoid. The twinning upon the albite and pericline types is sometimes associated with the Carlsbad type of twinning. The result of this may be realized by imagining two twin crystals like Fig. 121, set with their brachypinacoids in contact, but one twin being reversed, so that the basal planes of the one lie side by side with the macrodomes of the other. The pericline type of twinning is also met with, at times, in conjunction with the Baveno type.

The cleavages of the plagioclastic felspars are respectively parallel to the basal- and brachy- pinacoids, the basal cleavage being the more perfect. Other subordinate cleavages may be developed, but their existence is seldom indicated in microscopic sections.

Apart from the flame-reactions, first successfully employed by Szabo for the determination of the different species of felspar (p. 9), a similar end may be attained by measuring their angles of maximum extinction with reference to the edge (001 : 010) or $(0\,P : \infty\,\breve{P}\,\infty)$ in parallel polarized light. Such measurements are best made upon very thin cleavage plates, taken parallel in one case to (001) 0 P, in the other to (010) $\infty\,\breve{P}\,\infty$. These extinctions have been carefully investigated by Max Schuster and by other competent observers; and although it is often difficult to determine a very small extinction-angle with precision, still the results given, being in each case the mean of a great number of observations, must be regarded as well-established.

Fig. 124 represents a crystal of albite, or it may be taken as representing any triclinic felspar. In this figure the edge (001 : 010) is the line E E. On the basal plane a dotted line is drawn parallel to E E, and on the brachypinacoid there is another dotted line also parallel to E E. In measuring the angle of maximum extinction, either in a basal or a brachy-pinacoidal cleavage-plate or section, the edge E E, or the boundary line between twin lamellæ (albite type) parallel to E E, is brought exactly parallel to one of the spider-lines in the eye-piece, or exactly parallel to the principal section of one of the crossed Nicols. A reading should then be taken, and the stage, and with it the section or cleavage-plate, turned until the maximum extinction is attained. The angle through which the stage has been turned is the angle of extinction with reference to the edge (001 : 010).

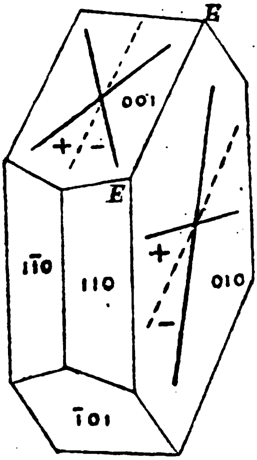

FIG. 124.

The extinction-angles of the principal felspars are diagrammatically shown in Figs. 125 and 126. In both of these figures the dotted line E E represents the edge (001 : 010), or the same line which is represented by E E in Fig. 124. Extinction-angles in sections of plagioclastic felspars cut obliquely to the planes of composition of the twin-lamellæ cannot be measured with any degree of precision, since in such sections the lamellæ lie in wedges over and under one another.

In sections of albite parallel to the brachypinacoid, the acute bisectrix (positive, c) emerges from the section more or less obliquely. The optic-axial angle varies somewhat from 90°. In albite and oligoclase the dispersion is $\rho < v$, while in labradorite and anorthite it is $\rho > v$.

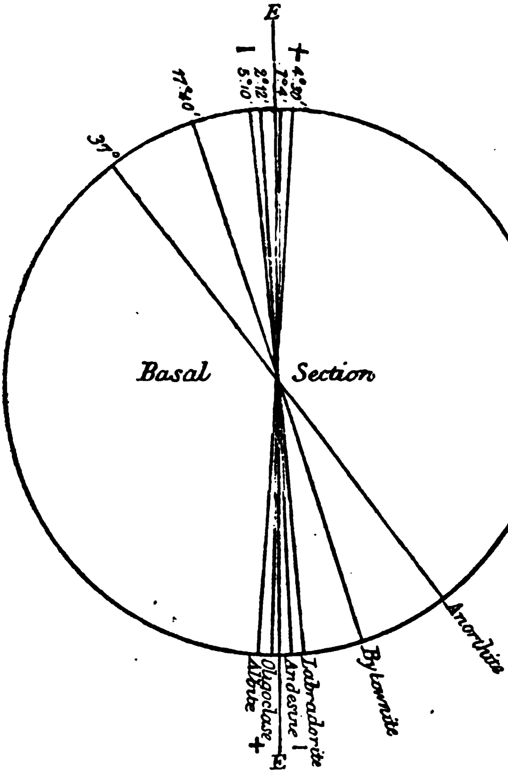

FIG. 125.

Cleavage-plates and sections of albite parallel to (010) show, when examined in convergent light, the dark bars of the optic normal and a bisectrix, intersecting in a point remote from the centre of the field. The poles of the axes emerge from the section outside the field, but in the diagonal position of the plate portions of the two systems of rings are visible. The dispersion is inclined and horizontal, but the latter is weak.

Basal sections show no interference-figure. Sections of oligoclase parallel to (010) exhibit the dark bars intersecting nearly in the centre of the field. The dispersion in oligoclase is very feebly inclined and feebly crossed. Sections of labradorite and bytownite parallel to the right brachypinacoidal face (010), and also in those parallel to (001), show a system of rings and an hyperbola, due to the oblique emergence of an optic axis just outside the field. The crossed dispersion is distinct, and there is feeble inclined dispersion. In anorthite a system of axial rings is seen in sections respectively parallel to the faces (010) and (001) near the margin of the field.

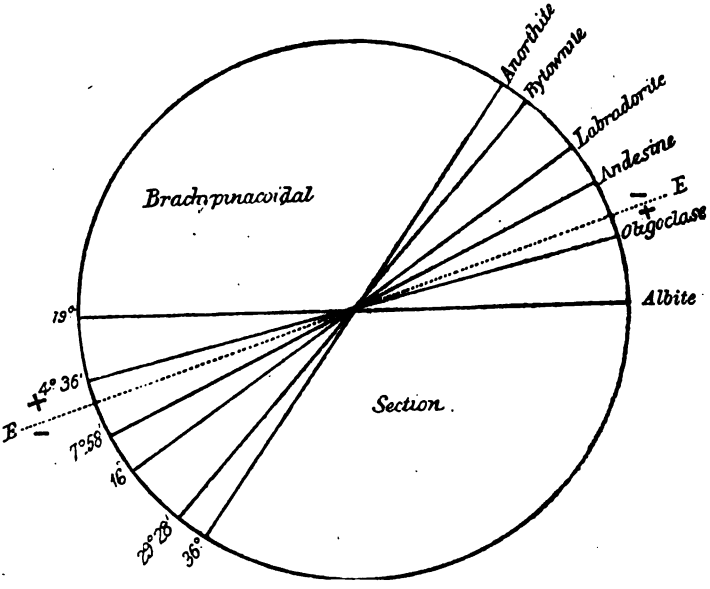

FIG. 126.

By alteration the plagioclastic felspars pass into kaolin; and in certain rocks, especially in those rich in nepheline, they are frequently converted into zeolitic matter. At times these felspars are altered into micas, such as muscovite, or, in the case of albite and oligoclase, possibly into paragonite. In the alterations a separation of silica in the form of quartz is of common occurrence. In some cases pseudomorphs composed of small quartz grains are met with. Epidote and calcite are also common among these alteration products of the plagioclastic felspars.

Kyanite,—$Al_2O_3SiO_2$,—is chiefly met with in crystalline schists, gneiss, eclogite, granulite, etc.. The mineral has a long-prismatic habit, and at times an almost fibrous character, especially in Rhætizite. Terminal faces are rare. The prisms are usually combinations of $\infty \bar{P} \infty$ (100), $\infty \breve{P} \infty$ (010), and ∞P (110); with these, other forms also frequently enter into combination. The angle (100) : (010)=106° 4′ and (100) : (110) =145° 13′. Sections transverse to the prisms are usually six-sided or rhomboidal, and the angles are often rounded.

Twinning is common, and occurs in several different ways, the most frequent being that in which the twin axis is normal to the brachypinacoid (010). Parallel to this face there is a very perfect cleavage.

By ordinary transmitted light kyanite appears colourless, or of pale-blue or greenish-blue tints. The colour, however, when present, is not always equally distributed.

Sometimes the crystals appear almost opaque through the presence of carbonaceous matter. The refractive index is high and the double refraction strong and negative. The optic-axial plane lies almost at right angles to the macropinacoid, and is inclined about 30° to the edge (100) : (010). The optic-axial angle is generally very large $2V = 82°$ to 83°. The dispersion is weak, $\rho > v$.

In sections parallel to (100) the extinction-angle is 30° to 31° measured from the edge (110 : 010), while in sections parallel to (010) measured from the same edge it is 7° to 8°.

The pleochroism is only perceptible in the more strongly-coloured crystals.

There are some few minerals of a more or less homogeneous character which the student will frequently meet with when examining sections of rocks under the microscope. Among these are—

Serpentine,—$H_2 Mg_3 Si_2 O_8$+aq.,—which, by transmitted light, appears of different shades of green or brown, the green kinds sometimes possessing a bluish tinge. Various structures are exhibited by serpentine, which have received the names "mesh-structure," "lattice-structure," etc. The structural differences are apparently dependent upon the nature of the mineral which, by its alteration, has given birth to the serpentine. The conversion of olivine into serpentine has already been described (p. 156). Other minerals, such as the amphiboles and pyroxenes, undergo similar alterations; but the serpentine resulting from their decomposition differs generally in structure from that which has been derived from the alteration of olivine, the mesh-structure usually characterizing the latter, while the former mostly exhibits the lattice-structure. The character of the mesh-structure is due to the irregular fissures by which crystals of olivine are usually traversed, and along which the serpentinous matter is first developed, and also to the similar incipient alteration on the boundaries of the olivine crystals. The cause of the lattice-structure, on the other hand, is to be found in the intersecting cleavages of the amphiboles and pyroxenes.

The ultimate structure of serpentine appears as a rule to be either fibrous or platy. The coarser fibres are stated to exhibit a biaxial character, the angle of the optic axes being wide, the double-refraction negative, and the bisectrix, $\mathfrak{a}$, situated at right angles to the axis of the fibre. Consequently the axis of least elasticity, $\mathfrak{c}$, is parallel to the length of the fibre. These characters are said to be best seen in chrysotile;

but they do not appear to be invariable, since, in the variety metaxite, the axis of least elasticity has been found to play the part of acute bisectrix, so that in this case the optical sign is positive. In the platy kinds of serpentine it is found to be negative again, and the axial angle is small.

Delessite, a hydrous silicate of alumina, iron, and magnesia, sometimes occurs pseudomorphous after amphibole and pyroxene. It is also met with in the cavities of vesicular rocks forming small amygdaloids. It mostly appears in fibrous aggregates or in pellets which have a radiating-fibrous and often a concentrically zoned structure, the latter being due to successive fibrous growths. In transmitted light delessite appears green, or occasionally brownish.

The double refraction is weak.

The directions of extinction are suggestive of a rhombic mineral. The axis of least elasticity lies parallel to the length of the fibres. Delessite shows more or less pleochroism.

Glauconite, which occurs plentifully in many rocks of sedimentary origin, and possibly in some others, is, as its name implies, of a green colour. It is essentially a hydrous silicate of protoxide of iron and potash, but the composition is very variable, alumina being usually present and occasionally a very small amount of soda. Between crossed Nicols it shows feeble double refraction or, in some cases, appears isotropic.

In the glauconitic sandstones the grains are often found to be casts of the interior of foraminiferal tests. Glauconite is completely decomposed in hot, concentrated hydrochloric acid. A variety occurring in a magnesian limestone in the valley of the Minnesota is, however, stated to be unaffected by this reagent.

Greenearth, or Celadonite, is a hydrous silicate of iron, alumina, magnesia, potash, and occasionally soda and lime, the latter being present as carbonates. It is of a deep olive- or apple- green, earthy, exceedingly soft, feels somewhat greasy, and adheres slightly to the tongue. In hot hydrochloric acid it turns, according to Naumann ("Elemente der Mineralogie," 10th ed.), first yellow, then colourless, and becomes completely decomposed, leaving a pulverulent residue of silica. According to Klaproth and Von Kobell (Dana's "System of Mineralogy," 5th ed.), it is not acted upon by hydrochloric acid. Green-earth occurs pseudomorphous after pyroxenic minerals, and is also found filling vesicular cavities in basic lavas.

Kaolinite,—Al_2O_3, 2 SiO_2, 2 H_2O,—is a common product of the alteration of felspars. The mineral crystallizes usually in six-sided colourless plates, which, when of moderate dimensions, show double refraction and optical characters generally resembling those of muscovite.

The ordinary earthy kaolin, when levigated, is seen to consist of very small and irregularly-bounded scales.

The mineral is optically negative; and, according to Rosenbusch, the axis of greatest elasticity, $\mathfrak{a}$, is normal or approximately normal to the basal plane or broad face of the crystal.

TABLES OF HARDNESS AND SPECIFIC GRAVITY OF THE PRINCIPAL ROCK-FORMING MINERALS.

Cubic System.

	Hardness.	Specific Gravity.
Analcime	5·5	2·1–2·28
Automolite	8·0	4·33–4·35
Chromite	5·5	4·4–4·6
Fluorspar	4·0	3·0–3·25
Garnets	7·0–7·5	3·4–4·3
Haüyne	5·0–5·5	2·27–2·5
Leucite	5·5–6·0	2·45–2·5
Magnetite	5·5–6·5	4·9–5·2
Pyrites	6·0–6·5	4·8–5·1
Rock Salt	2·0–2·5	2·1–2·2
Sodalite	5·5	2·28–2·34
Spinel	8·0	3·5–4·1

Hexagonal System.

	Hardness.	Specific Gravity.
Apatite	5·0	2·92–3·25
Calcite	3·0	2·6–2·8
Cancrinite	5·5–6·0	2·45
Chalcedony	7·0	2·59–2·64
Chlorite	1·0–3·0	2·65–2·97
Corundum	9·0	3·9–4·0
Dolomite	3·5–4·0	2·8–2·9
Graphite	1·0–2·0	2·0
Hematite	3·5–6·5	4·5–5·3
Ilmenite	5·0–6·0	4·3–5·21
Nepheline	5·5–6·0	2·55–2·61
Quartz	7·0	2·65–2·66
Tourmaline	7·0–7·5	3·0–3·24
Tridymite	7·0	2·28–2·33

TETRAGONAL SYSTEM.

	Hardness.	Specific Gravity.
Anatase . . .	6·0	3·8–3 9
Idocrase . . .	6·5	3·29–3·47
Melilite . . .	6·5	2·93
Rutile . . .	6·5	4·2–4·3
Scapolite . .	5·0–6·0	2·62–2·85
Tinstone . . .	6·0–7·0	6·8–7·0
Zircon . . .	7·5	4·4–4·7

RHOMBIC SYSTEM.

	Hardness.	Specific Gravity.
Andalusite . .	5·5–7·5	3·15–3·20
Anhydrite . .	3·0–3·5	2·89–3·0
Anthophyllite .	5·5	3·19–3·23
Aragonite . .	3·5–4·0	2·9–3·0
Bastite . . .	5·5	2·70
Bronzite . . .	5·5	3·19
Dichroite . .	7·0–7·5	2·56–2·67
Enstatite . .	5·5	3·1–3·3
Gedrite . . .	5·5	3·15–3·35
Hypersthene . .	5·0–6·0	3·15–3·39
Natrolite . .	5·0–5·5	2·17–2·26
Olivine . . .	6·0–7·0	3·23–3·56
Sillimannite . .	5·5–7·5	3·23–3·24
Staurolite . .	7·0–7·5	3·26–3·79
Talc . . .	1·0	2·56–2·80
Topaz . . .	8·0	3·51–3·57
Zoisite . . .	6·0–6·5	3·1–3·38

MONOCLINIC SYSTEM.

	Hardness.	Specific Gravity.
Actinolite . .	5·0–6·0	3·026–3·166
Augite . . .	5·0–6·0	2·88–3·5
Biotite . . .	2·5–3·0	2·8–3·2
Diallage . . .	4·0	3·23–3·34
Epidote . . .	6·0–7·0	3·32–3·49 (Piedmontite 3·52)
Hornblende . .	5·0–6·0	3·1–3·3
Lepidolite . .	2·5–4·0	2·83–2·89
Lepidomelane. .	2·5–3·0	2·8–3·2
Muscovite . .	2·0–2·5	2·83–2·89
Orthoclase . .	6·0	2·53–2·62
Ottrelite . . .	6·0–7·0	3·26
Paragonite . .	2·0–2·5	2·778
Phlogopite . .	2·5–3·0	2·75–2·97
Selenite . . .	1·5–2·0	2·0–2·4
Sphene . . .	5·0–5·5	3·4–3·6
Tremolite . .	5·0–6·0	2·93–3·0
Wollastonite . .	4·5–5·0	2·78–2·90

TRICLINIC SYSTEM.

	Hardness.	Specific Gravity.
Albite . .	6·0–6·5	2·61–2·63
Andesine .	5·0–6·0	2·65
Anorthite .	6·0	2·73–2·75
Axinite .	6·5–7·0	3·27–3·30
Bytownite .	6·0	2·70–2·73
Kyanite .	5·0 on 100–7·0 on 010	3·48–3·68
Labradorite .	6·0	2·68–2·70
Microcline .	6·0	2·54–2·57
Oligoclase .	6·0–7·0	2·62–2·65

TABLES OF OPTICAL CONSTANTS OF THE PRINCIPAL ROCK-FORMING MINERALS.

CUBIC SYSTEM.

	Sign	Refractive Index.		Ray.	Minerals sometimes showing Anomalous Double Refraction, marked D.
		ω	ε		
Almandine .	...	1·772	...	red	D. rare
Analcime .	...	1·4874	...	red	D.
Chromite .	...	2·0965	...	...	...
Essonite .	...	1·741	...	red	D.
Grossular .	...	1·7468	...	yellow	D.
Haüyne .	...	1·4961	...	yellow	...
Leucite .	±	1·508	1·509	...	D. Isotropic at 500° C.
Pyrope . .	...	1·8141	...	yellow	...
Sodalite .	...	1·4858	...	yellow	...
Spinel . .	...	1·7150	...	yellow	...

HEXAGONAL SYSTEM.

	Sign.	Refractive Index.			
		Red.		Yellow.	
		ω	ε	ω	ε
Apatite .	—	...	...	1·6388	1·6346
Calcite . .	—	...	...	1·6585	1·4864
Cancrinite .	—	1·5244	1·4955	...	...
Chlorite .	+ —	1·577 1·576	1·576 1·575	...	...
Corundum .	—	1·767	1·759	1·7690	1·7598
Dolomite .	—	...	...	1·6817	1·5026
Nepheline .	—	...	...	1·5376	1·5416
Quartz . .	+	...	...	1·54418	1·55328
Tourmaline .	—	1·6444	1·6240	1·6397	1·6208

TETRAGONAL SYSTEM.

	Sign.	Refractive Index.			
		Red.		Yellow.	
		ω	ε	ω	ε
Anatase .	−	2·511	2·476	2·554	2·493
Idocrase .	−	...	...	1·719	1·718
Melilite .	−	1·6312	1·6262	1·6339	1·6291
Rutile . .	+	2·5671	2·8415	2·6158	2·9029
Scapolite .	−	1·566	1·545	1·594	1·558
Tinstone .	+	1·9793	2·0799	1·9966	2·0934
Zircon . .	+	1·92	1·97	1·9313	1·9931

RHOMBIC SYSTEM.

	Sign.	Indices.			Ray.	Optic Axial Angle.		
		min. α	mean β	max. γ		apparent 2 E	real 2 V	Optic Axial Plane and Dispersion.
Andalusite .	—	1·632	1·638	1·643	red	... ...	83°–85°	010
Anhydrite .	+	1·571	1·576	1·614	...	71°10′–71°20′	...	100
Anthophyllite .	+	...	1·636	...	red	$2H_a = 81°$	...	010
Aragonite .	—	1·5301	1·6816	1·6859	yellow	... ...	18°	100 $\rho < v$
Bastite . .	—	...	1·5–1·6	...	...	... ...	20°–90°	100 $\rho > v$
Bronzite . .	+	...	1·668	...	red	... ...	...	010 $\rho \lesseqgtr v$
Dichroite . .	—	1·535	1·541	1·546	yellow	64°–150°	...	100 $\rho < v$
Enstatite . .	+	...	...	...	...	$2H_o = 133°8'$	...	010 $\rho < v$
Gedrite . .	—	...	...	...	...	$2H_a = 47°–82°$	...	010
Hypersthene .	—	1·7158	$\begin{Bmatrix} 1·7125 \\ 1·685 \end{Bmatrix}$	1·7270	...	$2H_a = 59°20'–98°22'$	...	010 $\rho > v$
Natrolite . .	+	1·4768	1·4797	1·4887	red	$93°28'_{\rho} \ldots 95°41'_{v}$	59°29′	010 $\rho < v$
Olivine . .	+	1·661	1·678	1·697	yellow	... ...	87°46′	001 $\rho < v$
Sillimannite .	+	...	1·66	...	red	$44°_{\rho} \ldots 37°_{v}$	...	100
Staurolite .	—	...	1·7526	...	red	89°	...	100
Talc . . .	—	...	...	...	...	$17°_{\rho} \ldots 16°_{v}$	...	100
Topaz . .	+	1·612	1·614	1·621	yellow	70°–125°	...	010 $\rho > v$
Zoisite . .	+	...	1·69–1·70	...	red	Cir. 0°–100°	...	010 $\rho < v$ or 001 $\rho > v$

MONOCLINIC SYSTEM.

	Sign.	Indices.			Ray.	Optic Axial Angle.		
		min. α	mean β	max. γ		apparent 2E	real 2V	Optic Axial Plane and Dispersion.
Actinolite .	−	...	1·629	...	yellow	... ...	80°4′	010 $\rho<v$
Augite . .	+	1·673	1·679	1·703	yellow	... ...	61°	010
Biotite . .	−	...	...	...	...	Cir. 0°–72°30′	...	010 $\rho<v$
Diallage . .	+	...	...	...	...	... ...	47°51′	... ...
Epidote . .	−	1·731	1·754	1·761	red	... ...	73°36′	010 $\rho>v$
Hornblende .	±	...	1·642	...	red	... ...	85°	010 $\rho<v$
Lepidolite .	−	...	...	...	...	74°–76°30′	...	⊥010 $\rho>v$
Lepidomelane .	−	...	...	...	...	... ...	0° ⟶	... ...
Muscovite .	−	1·537	1·541	1·572	yellow	... ...	40°–70°	⊥010 $\rho>v$
Orthoclase .	−	1·519	1·524	1·526	yellow	0°–40°	...	⊥010 $\rho>v$ ||010 $\rho<v$ Horiz. disp. Incl. disp.
Ottrelite . .	+	...	1·718	...	...	... ...	...	010 $\rho>v$
Paragonite .	−	...	...	...	...	... ...	...	⊥010 $\rho>v$
Phlogopite .	−	...	...	...	...	... ...	...	010 $\rho<v$ (in Zinnwaldite $\rho>v$)
Selenite . .	−	1·521	1·527	1·530	yellow	61°24′	...	010
Sphene . .	+	...	1·903	...	red	53°30′	...	010 $\rho>v$
Tremolite .	−	1·6065	1·6233	1·6340	yellow	... ...	81°22	010 $\rho<v$
Wollastonite .	+	...	...	...	...	$70°40'_{\rho} \ldots 68°24'_{v}$	...	010

TRICLINIC SYSTEM.

	Sign.	Indices.			Ray.	Optic Axial Angle.		
		min. α	mean β	max. γ		apparent 2E	real 2V	Optic Axial Plane and Dispersion.
Albite . .	+	...	1·537	...	red	...	...	... ...
Anorthite .	—	...	1·573	...	...	...	...	... ...
Axinite . .	—	1·6720	1·6779	1·6810	red	...	71°38′–74°17′	$\perp \bar{1}10$ Incl. and Horiz.
Kyanite . .	—	...	1·720	...	red	...	82°–83°	cir. $\perp 100$ $\rho > v$
Labradorite .	+	...	...	...	...	...	...	... ...
Microcline .	...	...	...	...	...	...	87°–89°	82°–83° to 010

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ROCK-FORMING MINERALS.

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